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Propeller Blade Measurements for HMCS NIPIGON

D.J. Noble

Defence R&D Canada

Technical Memorandum
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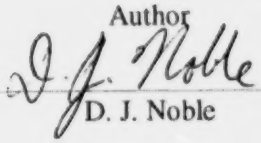

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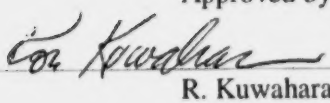

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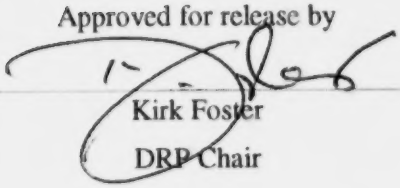

Kirk Foster

DRP Chair

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Abstract

This report describes results obtained for the differences in the blade geometry of the propellers of HMCS NIPIGON based on detailed blade measurements performed with a pitchometer and ultrasonic thickness measuring equipment. Visual inspection of the blades made while the ship was in dry dock for a previous sea trial revealed signs of significant surface wear and damage. The measurements were requested by DRDC Atlantic after the ship went out of service to determine if the geometric differences between the blades of each propeller could have caused the unexpectedly large differences in the cavitation inception performance of individual blades observed during the sea trial.

The results show significant differences in the key geometric parameters of blade sections, especially in the pitch angle, chord length and rake of measured sections at outer radii. Of the section differences obtained from the blade measurements, the pitch angle increases of more than two degrees relative to design approaching the blade tips are expected to have the largest effect on inception of cavitation in this region. Examination of the nose shapes of the leading edges on selected blades also revealed flats and overly sharp edges near locations where cavitation was observed to form during the sea trial. The sharpness of the leading edges can also have a significant effect on inception speeds, and is likely the cause of the flow separation and formation of vortex cavitation observed along the leading edges of the blades.

Résumé

Le présent rapport décrit les résultats d'une étude sur les différences de géométrie des pales des hélices du NCSM NIPIGON à partir des mesurages effectués à l'aide d'une jauge de pas et d'instruments de mesure de l'épaisseur aux ultrasons. Une inspection visuelle des pales effectuée pendant que le navire était en cale sèche à la suite d'un essai en mer a révélé des signes de dommages et d'usure de surface importants. Après le désarmement du navire, le RDDC Atlantique a demandé qu'on prenne des rélevés des dimensions des hélices pour déterminer si les différences de géométrie entre les pales des hélices pouvaient causer les écarts étonnamment importants dans la vitesse d'apparition du phénomène de cavitation d'une pale à l'autre observés au cours de l'essai en mer.

Les résultats ont révélé des différences importantes dans les paramètres géométriques clés des sections de pales, surtout en ce qui concerne l'angle du pas, la longueur de corde et l'angle d'attaque des sections mesurées sur le congé extérieur. De toutes les différences de section obtenues à partir des mesurages, ce sont les augmentations de l'angle de pas de plus de deux degrés par rapport à la valeur de calcul, à l'approche du bout de la pale, qui devraient avoir la plus grande incidence sur l'apparition de la cavitation à cet endroit. L'examen de la forme des bords d'attaque de quelques pales a aussi révélé qu'ils étaient plats et trop aigus près des endroits où la cavitation se formait pendant les essais en mer. Le fait que les bords d'attaque soient aigus peut aussi avoir une incidence importante sur les vitesses d'apparition de la cavitation, et est susceptible de causer la séparation de l'écoulement et la formation de la cavitation tourbillonnaire observée le long des bords d'attaque des pales.

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Executive Summary

This report describes results of detailed measurements of the propeller blades of HMCS NIPIGON performed by FMF Cape Scott at the request of DRDC Atlantic after the ship went out of service in year 2000. Pitchometer and ultrasound thickness measurements were performed to quantify suspected differences in geometry between the blades of each propeller that may have led to abnormally large differences in cavitation inception speeds observed on different blades during an earlier sea trial performed in October, 1997. The sea trial was organized as part of the Co-operative Research Navies (CRNAV) Project on In-Service Propeller Performance with the purpose of quantifying the changes to inception speeds of propeller cavitation occurring during turning manoeuvres and operations in a seaway relative to the ideal conditions of straight-ahead sailing in calm seas.

The measurements show significant differences in the key geometric parameters of blade sections mostly in the outer 20% of the blades of both propellers when compared to the design geometry. Differences in the pitch angle, chord length, skew angle and total rake of measured sections generally increase to maximum values moving towards the blade tips. Of these differences, the significant increases in the pitch angle of outer radius sections of more than two degrees relative to design on the port propeller would have the most significant effect on inception of cavitation in the tip region. The variation in over-pitching of outer sections combined with the visible differences in the nose shapes of section leading edges are the likely causes of the large inter-blade differences in cavitation inception speeds observed during the sea trial.

These results emphasize the need to ensure that propeller blades designed for improved cavitation performance, either newly-manufactured blades or older blades suspected to have surface wear and damage, maintain close tolerances relative to the design geometry. In particular, section geometries near the blade extremities should be measured and made to conform closely to design specifications. Unfortunately, even the best ISO Standards for manufacturing tolerances of marine propeller geometry do not specify requirements to be met for the detailed geometry near the tips and for the root filleting of propeller blades where cavitation often forms. In the past, these areas either were not included or were inadequately defined in specifications to the manufacturer. Strict adherence to detailed specifications for the design geometry is particularly important for propellers of naval vessels because of the significant increase in radiated noise levels generated when cavitation starts.

This measurement program also shows a need for improvements to blade measuring devices and procedures both to decrease the length of time required to perform the measurements and to improve the accuracy of the measurements, particularly at the blade extremities. Based on the current measurements, development is required of a larger optical scanning device with digital readouts or direct input to computers that can be accurately positioned relative to the blades and more quickly measure the relative location of a large number of surface points around the tips and leading edges.

Noble, D.J. 2002. Propeller Blade Measurements for HMCS NIPIGON.
DRDC Atlantic TM 2002-093. Defence R & D Canada - Atlantic.

Sommaire

Le présent rapport décrit les résultats du mesurage détaillé des pales d'hélices du NCSM NIPIGON effectué par l'IMF Cape Scott à la demande du RDDC Atlantique après le désarmement du navire en 2000. Des relevés à la jauge de pas et aux instruments de mesure de l'épaisseur aux ultrasons ont été effectués pour mesurer s'il y avait, comme on le pensant, des différences de géométrie à l'origine des écarts anormalement importants dans les vitesses d'apparition de la cavitation observés sur diverses pales pendant l'essai en mer d'octobre 1997. Cet essai avait été organisé dans le cadre du programme de recherche en coopération sur les navires de guerre (CRNAV) pour étudier le rendement des hélices des navires en service et quantifier les variations de la vitesse d'apparition de la cavitation des hélices durant les manœuvres giratoires et les opérations en voie maritime par rapport aux conditions idéales de navigation en ligne droite par mer calme.

Les relevés montrent des différences importantes dans les paramètres de géométrie clés des sections de pales, surtout dans les 20 % de surface constituant l'extrémité des deux hélices, en comparaison avec la géométrie de calcul. Dans l'ensemble, plus on s'avance vers le bout des pales, plus les différences au niveau de l'angle de pas, de la longueur de corde, de l'angle d'inclinaison et de l'angle d'attaque total des sections mesurées augmentent vers leurs valeurs maximales. De toutes ces différences, ce sont les importantes augmentations (plus de deux degrés par rapport aux valeurs de calcul) dans l'angle de pas des sections de congé extérieur de l'hélice bâbord qui auraient la plus grande incidence sur l'apparition de la cavitation dans le bout des pales. Les écarts dans les données de surinclinaison des sections extérieures combinés avec les différences visibles dans la forme du nez des bords d'attaque de section sont les causes probables des importantes dissimilitudes en ce qui concerne la vitesse d'apparition de la cavitation observée d'une pale à l'autre durant les essais en mer.

Ces résultats mettent en évidence la nécessité que les pales d'hélice conçues pour mieux résister à la cavitation, qu'il s'agisse de pales neuves ou de vieilles pales endommagées ou usées en surface, respectent des tolérances serrées par rapport à la géométrie de calcul. En particulier, la géométrie des sections près de l'extrémité des pales devrait être mesurée et maintenue de manière à se conformer de près aux spécifications de calcul. Malheureusement, même les meilleures normes de tolérance de fabrication ISO en matière de géométrie des hélices de navire ne contiennent pas d'exigences sur la géométrie détaillée du bout et du rayon de congé des pales d'hélices, où la cavitation se produit souvent. Par le passé, ces endroits n'étaient pas inclus ou adéquatement définis dans les spécifications de fabrication. Il est particulièrement important de respecter les spécifications relatives à la géométrie de calcul des hélices des navires de guerre parce que l'apparition de la cavitation fait augmenter de façon importante les niveaux de bruit.

Ce programme a aussi permis de découvrir qu'il fallait améliorer les dispositifs et les procédures de mesurage des hélices pour, d'abord, diminuer le temps requis pour les mesures et, ensuite, pour améliorer la précision des mesures, particulièrement à l'extrémité des pales. Si l'on se fie aux relevés qui ont été faits, il faut mettre au point un dispositif de balayage optique plus gros avec affichage numérique ou avec entrée directe des données sur ordinateur qui peut être positionné avec précision contre les pales et mesurer plus rapidement l'emplacement relatif d'un grand nombre de points de surface près du bout et du bord d'attaque des pales.

Noble, D.J. 2002. Propeller Blade Measurements for HMCS NIPIGON.
RDDC Atlantique TM 2002-093. R et D pour la Défence du Canada - Atlantique.

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Acknowledgements

The author would like to thank all of the personnel at FMF Cape Scott involved with the propeller blade measurements for their full cooperation and support over the extensive 8 month period between May and December 2000. In particular, special thanks goes to John Jornitz of Shop 10080 for performing and recording the vast majority of the pitchometer measurements and for his patience and effort throughout this period to ensure that the measurements were as accurate and consistent as possible for all fourteen blades.

1. Introduction

A sea trial was performed on HMCS NIPIGON in October 1997 as part of the Co-operative Research Navies (CRNAV) Project on In-Service Propeller Performance. This CRNAV project is jointly funded by DRDC Atlantic, the Royal Netherlands Navy (RNIN), the Royal Australian Navy (RAN), and the Maritime Research Institute Netherlands (MARIN). The purpose of the trial was to quantify changes to propeller cavitation inception speeds occurring during turning manoeuvres and operations in a seaway relative to the ideal conditions of straight-ahead sailing in calms seas. A brief visual inspection of the ship's propeller blades was made prior to the trial when the ship was in dry dock for pre-trial fit-out work. At that time, visible signs of surface wear and damage were observed, as well as inter-blade differences in the shapes of edges especially near the blade tips. There was insufficient time to have the propellers removed and measured prior to the sea trial.

The results of the cavitation viewing trial on HMCS NIPIGON suggested that differences in the inter-blade geometry of propellers were likely responsible for the abnormally large differences in cavitation inception speeds observed on different blades during trial runs. The propellers were designed by DRDC Atlantic for optimal inception speeds of both sheet and tip vortex types of cavitation. Although previous model tests confirmed the cavitation performance of the design geometry, the lowest inceptions speeds obtained on most blades under ideal conditions during the trial were well below design expectations. Trials results also showed blade-to-blade variations in inception speeds that were much larger than those typically observed on propellers of other ships during previous sea trials. Even for straight runs in calm seas, inception speed differences up to six knots were observed for similar types of cavitation forming on different blades of one propeller. Other runs with the ship performing calm-sea turning circle manoeuvres and straight runs in moderate seas showed similarly high levels of inter-blade variation.

To help explain these inter-blade differences in cavitation performance, DRDC Atlantic had FMF Cape Scott in the Halifax Navy Dockyard perform detailed measurements of the propeller blades after the ship went out of service early in year 2000. Measurements of the geometry of all seven blades on each of the port and starboard propellers were carried out between May and December 2000 using a combination of surface measurements with a pitchometer device and ultrasonic thickness measuring equipment. This report summarizes the results of these measurements. The results can be used in future work performed for the CRNAV Project to assess the significance of differences obtained between analytical predictions, model scale experiments and full scale observations.

The details of the blade measurement program performed by FMF Cape Scott are described in Section 2. This is followed in Section 3 by a summary of results for inter-blade differences in key geometric parameters, blade outline shapes and the geometry of constant radius blade sections. This section also contains some limited observations of differences in the relative sharpness of the leading edges of outer radius sections on selected blades. The significance of the key results is discussed in Section 4 and conclusions resulting from this work are provided in Section 5.

2. Measurement Program

This section describes the program of measurements performed with the twin, seven-bladed, fixed-pitch propellers of HMCS NIPIGON. The procedures used for pitchometer measurements of the relative locations of surface points of each side of the blades and the ultrasound thickness measurements are described. The section concludes by outlining the procedures used to simplify data acquisition and processing, in order to ensure a reasonable level of consistency throughout the measurements for all 14 blades of two propellers.

2.1 Pitchometer Measurements

A standard pitchometer device was used to measure the relative location of surface points on constant radius cylindrical sections of the propeller blades. A diagram of a generic pitchometer positioned on a propeller hub is provided in Figure 1. For measurements performed on each side of the blades, the propellers were mounted on a rigid horizontal platform with one of the parallel flat surfaces on each end of the hub resting securely on the platform. The pitchometer was then centred and clamped in position on the upper hub face such that the horizontal measuring arm of the device rotated about the centre axis of the hub.

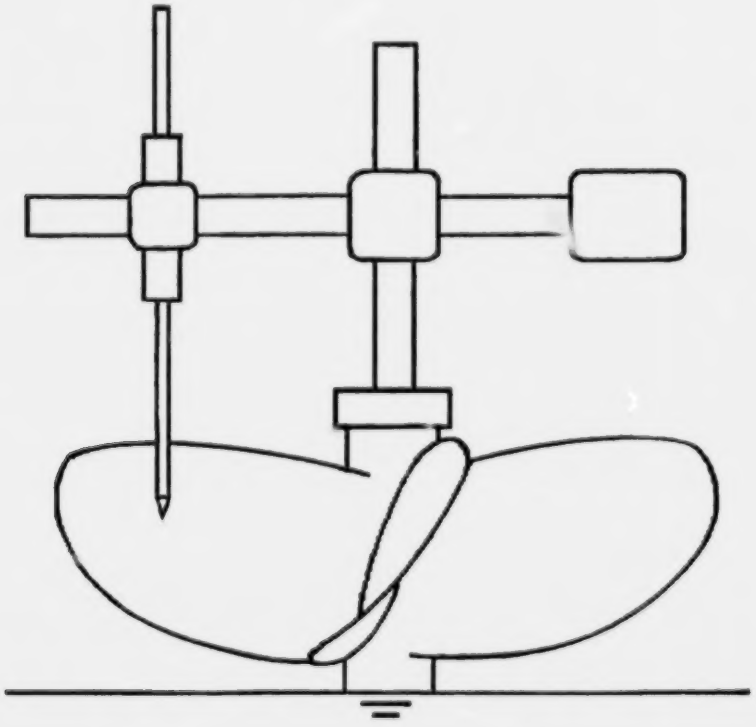


Figure 1. *Diagram of a Generic Pitchometer Centred on a Propeller Hub.*

The horizontal arm of the pitchometer could be rotated to any desired angle in a plane parallel to the propeller rotation plane. The horizontal arm also had a sliding vertical arm that could be positioned at any desired radius and moved on a vertical axis until the sharp pointer located at one end of the arm contacted the blade surface. In this way, the pitchometer was used to measure the relative vertical distances of points at a fixed set of angular stations from leading to trailing edges on fixed radius sections of the blades.

Due to the significant overlap of adjacent blades of this propeller, it was not possible to measure vertical distances to some points approaching one edge of most sections of the blade with the usual straight pointer. It was necessary to have a new pointer machined that could be horizontally offset by a pre-set angle at each measurement radius. The shape of the new offset pointer is shown in Figure 2. It had a circular cylindrical section at the top that inserted in the vertical measurement arm of the pitchometer, and then was bent 90 degrees to the horizontal and then back 90 degrees to a vertical section coming to a point at the end. The offset pointer could be adjusted by rotating it in the pitchometer's vertical arm to an angular displacement sufficient to allow all section points to be reached. For each fixed radius section measured, a reference point in the middle of one blade was marked that could be reached with both the straight and offset pointers. The pitchometer's angular scale was then used to determine the angular displacement between measurements made with the two pointers at the radius of the reference point. This angular offset was then used to adjust the angular coordinates recorded to a common reference over the surfaces of all blades.

Both the radial and vertical distances were recorded using a digital display in millimetres. Although this display provided a read-out of up to two decimal places to the nearest hundredth of a millimetre, the last decimal place for vertical distances was observed to vary several hundreds of a millimetre depending on how much pressure was applied to the metal pointer when it contacted the surface. An attempt was made to minimize this variation by inserting a piece of paper between the pointer and the surface. The pointer was then lowered to contact the paper with just enough pressure to hold it firmly in place, and then the vertical distance was adjusted slightly upward until the paper could just be removed.

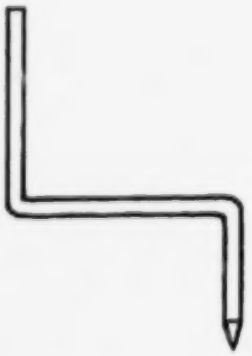


Figure 2. *Diagram of the New Offset Pointer.*

The angular measurements were read off circular vernier scales located around the centre axis of the device. This required measurement personnel to access the limited spaces between the blades before taking each reading. The vernier consisted of two scales, a larger scale covering 360 degrees that could easily be read to the nearest tenth of a degree, and a magnified scale with which the first reading could be further refined to the nearest hundredth of a degree. Given the large number of readings required on each side of 14 blades and the significant time required to make these readings, the angles were only recorded to the nearest tenth of a degree. The angles of surface points used for measurements were set as fixed percentages of the angle between the leading and trailing edges of each section. The angular spacing used between corresponding points on different blades, or on opposite sides of the same section, could then differ by one-tenth of a degree due to setting accuracy alone.

The measured vertical distances to surface points on each side of the blades were relative to reference planes for the pitchometer device that were parallel to the rotation plane used for the design blade geometry. The drawings for the propeller provided the location of the design rotation plane relative to the parallel end faces of the hub. In order to translate recorded distances on each side of the blades to a common design reference plane, the vertical distances to the hub end faces were also measured with the pitchometer.

Despite the best efforts to transform vertical measurements made on each side to a common reference, subsequent analysis of the measurements often showed the two sides of many fixed radius sections either intersecting with a small amount of crossover or having a slight gap at their trailing edges. These mismatches varied somewhat from blade-to-blade and section-to-section, with the largest differences occurring on the much thinner outer radius blade sections. This could have been due to a combination of the reference measuring planes of the pitchometer on each side not being completely parallel and the limited accuracy of the vertical measurements made with the metal pointers described earlier in the section.

2.2 Ultrasound Thickness Measurements

In an attempt to eliminate trailing edge mismatch and allow both sides of measured sections to meet at the proper thickness, an ultrasonic measuring device was used to determine the thickness normal to the blade surface at the 50 percent angular station. This location was close to the mid-chord point where sections reach their maximum thickness. This device was used previously by FMF Cape Scott to measure the thickness of metal surfaces on CF ships and submarines.

The point near mid-chord was selected since the surfaces on both sides at this location are very nearly parallel to their chord lines. It is then a simple matter to use the measured pitch angle of sections to resolve the ultrasound thickness measured normal to the surface into the vertical direction in order to compare with the vertical thickness resulting from pitchometer measurements. The thickness distribution over an entire section was then adjusted up or down to match the resolved vertical component of the ultrasound thickness obtained at the 50% angular station. Depending on whether the section was thicker or thinner than obtained with ultrasound, half of the vertical thickness difference was respectively added to or subtracted from the measured vertical coordinates obtained with the pitchometer on each side of the section. This process was found to significantly reduce the trailing edge mismatch.

2.3 Data Acquisition and Processing

Once the pitchometer was centred and clamped on the hub, the horizontal radius scale was then calibrated using a ruler of known length positioned along a horizontal radial out from the hub centre. The relative locations of the blade tips were then measured and entered into predefined boxes of a Microsoft Excel spreadsheet table similar to Table 1 provided below. Table 1 contains data recorded for the actual tip radius, vertical coordinate Z and tip angular location for blades marked with letters A through G on the face or downstream side of the starboard propeller. These data were measured again with essentially identical tip radii and angular spacing when the starboard propeller was flipped to measure the back or upstream side of corresponding blades marked with the numbers 1 through 7.

After the blade tips were measured, the coordinates of surface points located on selected fixed radius sections on the same side of each blade were measured and entered into other tables that were set up in the same Excel spreadsheet. A separate Excel file was created for measurements performed on one side of each propeller and data entry tables were provided using a separate worksheet or page for each of the seven blades. A portion of a sample data entry table for blade A is provided in Table 2. The actual measured data were entered into the fields marked with dark outlines in Table 2 with the rest of the fields either predefined or automatically calculated using Excel formulas based on the data entered.

As shown in Table 2, target radius stations were ordered from tip to root on each blade and defined at fixed fractions of the design tip radius R. The complete set of 13 radius fractions selected were r/R = 0.975, 0.95, 0.9, 0.85, 0.8, 0.75, 0.7, 0.65, 0.6, 0.5, 0.4, 0.3 and 0.25. Angles of section surface points were set at fixed percentages of the chord angular extent from leading to trailing edge with closer spacing used near the leading edge. First the leading and trailing edge angles were measured and entered, and then the resulting chord angular extent was determined automatically and displayed on the worksheet. The vertical coordinates were then measured using 25 target angles at angular percentages of 0, 1, 2, 3, 5, 7.5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, and 100. Target angles were also automatically calculated and displayed on the worksheet. As mentioned earlier, the actual angles were set to only the nearest tenth of a degree.

Blade	Measured Tip Radius [mm]	Measured Tip Z [mm]	Measured Tip Angle [deg.]
A	1676.70	-111.50	98.900
B	1676.00	-120.70	151.000
C	1676.50	-120.50	202.000
D	1676.55	-121.43	253.400
E	1676.30	-117.00	304.600
F	1675.90	-117.90	356.000
G	1676.70	-118.90	47.700

Table 1. *Sample of Recorded Blade Tip Measurements for the Starboard Propeller.*

BLADE A

RADIUS FRACTION		RADIUS MM	L.E. DEG.	T.E. DEG.	CHORD ANGULAR EXTENT DEG.	PERCENTAGE OF CHORD ANGULAR EXTENT => L.E. 0%	1%	2%	3%
0.975	TARGET	1634.59	87.800	107.400	19.600	TARGET DEG. 87.800	87.996	88.192	88.388
	ACTUAL	1634.59				ACTUAL DEG. 87.800	88.000	88.200	88.400
						ACTUAL Z MM -0.15	-4.80	-7.67	-10.20
0.95	TARGET	1592.68	83.000	110.300	27.300	TARGET DEG. 83.000	83.273	83.546	83.819
	ACTUAL	1592.68				ACTUAL DEG. 83.000	83.300	83.600	83.900
						ACTUAL Z MM 51.32	44.94	41.90	38.62
0.9	TARGET	1508.85	75.800	113.100	37.300	TARGET DEG. 75.800	76.173	76.546	76.919
	ACTUAL	1508.85				ACTUAL DEG. 75.800	76.200	76.600	76.900
						ACTUAL Z MM 133.10	124.44	119.97	114.42
0.85	TARGET	1425.03	70.700	113.900	43.200	TARGET DEG. 70.700	71.132	71.564	71.996
	ACTUAL	1425.03				ACTUAL DEG. 70.700	71.100	71.600	72.000
						ACTUAL Z MM 195.88	186.80	179.34	173.80
0.8	TARGET	1341.20	66.200	114.300	48.100	TARGET DEG. 66.200	66.681	67.162	67.643
	ACTUAL	1341.20				ACTUAL DEG. 66.200	66.700	67.200	67.600
						ACTUAL Z MM 255.88	246.23	237.40	232.46
0.75	TARGET	1257.38	62.600	114.500	51.900	TARGET DEG. 62.600	63.119	63.638	64.157
	ACTUAL	1257.38				ACTUAL DEG. 62.600	63.100	63.600	64.200
						ACTUAL Z MM 307.91	296.65	288.18	279.63
0.7	TARGET	1173.55	59.800	114.400	54.600	TARGET DEG. 59.800	60.346	60.892	61.438
	ACTUAL	1173.55				ACTUAL DEG. 59.800	60.300	60.900	61.400
						ACTUAL Z MM 353.22	342.39	331.89	323.78
0.65	TARGET	1089.73	57.600	113.900	56.300	TARGET DEG. 57.600	58.163	58.726	59.289
	ACTUAL	1089.73				ACTUAL DEG. 57.600	58.200	58.700	59.300
						ACTUAL Z MM 391.81	376.90	367.29	357.44

Table 2. *Portion of Sample Spreadsheet Used to Record Blade Surface Measurements.*

The worksheet for each blade was also set up to automatically display a chart showing the measured points on each section joined together by a smoothed line as the data were entered. Figure 1 below is a sample chart produced from measurements on the face side of blade A of the starboard propeller. These charts helped the measurer to catch obvious typing errors made during data entry. As a further check on results, DRDC Atlantic retrieved copies of the spreadsheets at regular intervals during the measurements and made a closer inspection of the data using additional charts for each radius to determine if there were any questionable data points. If any were found, then these points were re-measured for verification.

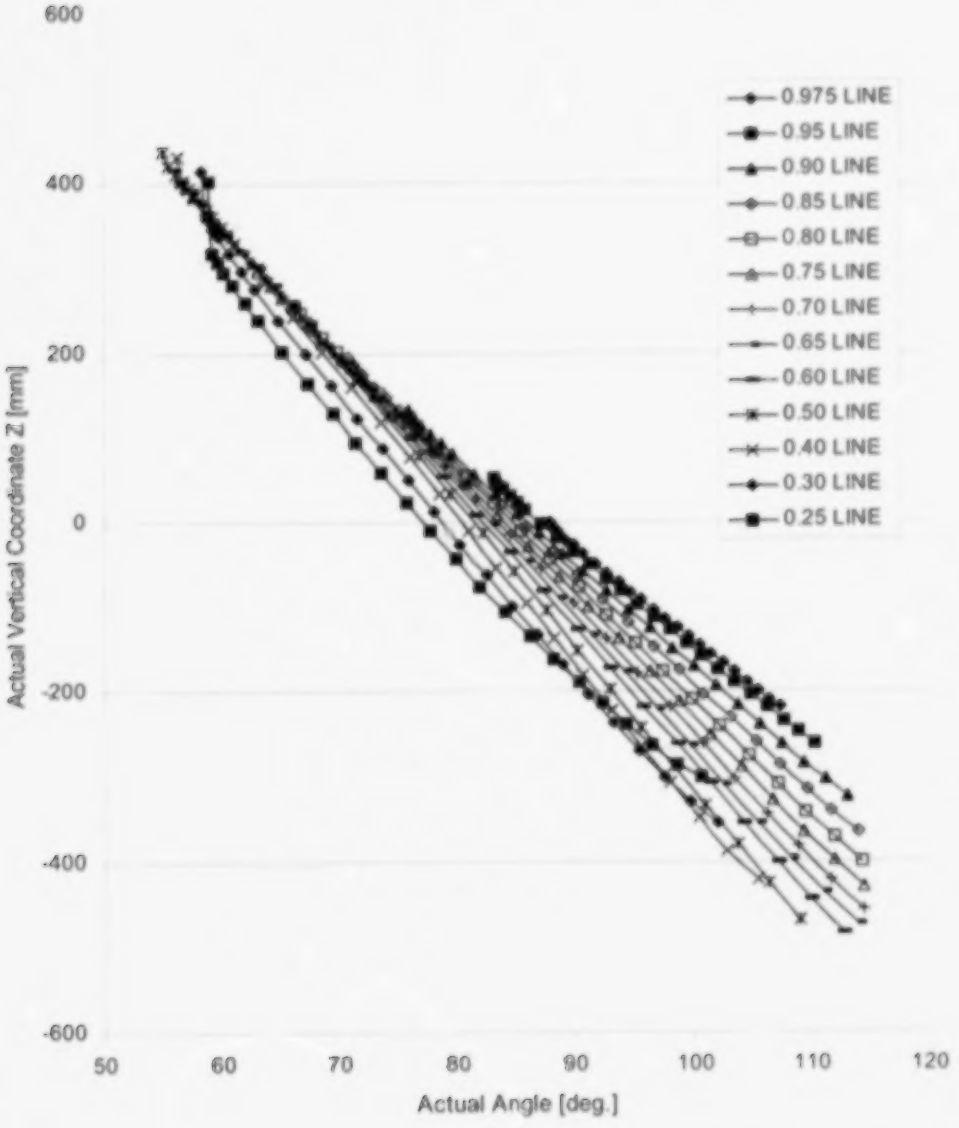


Figure 3. *Sample Chart of Face Surface Measurements on Blade A of the Starboard Propeller.*

3. Results of Blade Measurements

The results obtained from the blade measurement program are presented in this section through comparisons of the geometry of measured blades to each other and to the design blade geometry. For all seven blades of the port and starboard propellers, comparisons are provided for the radial distributions of key geometric parameters, projected views of the blade edge outlines, and expanded views of constant radius blade sections. The section concludes with a description of differences observed in the relative sharpness of leading edge shapes for three selected blades of the port propeller that were used for cavitation observations during the sea trial.

3.1 Radial Distributions of Key Geometric Parameters

First, the radial distributions obtained for the pitch angle, chord length, skew angle and total rake of measured sections are compared to each other and to the corresponding distributions for the design blade geometry. Figure 4 illustrates the pitch angle ϕ, chord length c, skew angle θ_s and the total rake Z_t of an expanded or flattened section in the Z-rθ plane using cylindrical axial, radial and angular coordinates Z, r and θ. Pitch angle is defined as the angle that the chord line of a fixed radius section makes with the propeller rotation plane. Chord length is the distance along the chord line between the leading and trailing edges. Skew angle is the angle to the section's mid-chord in a plane parallel to the propeller rotation plane, measured from the plane containing the shaft axis and the radial reference line of the blade. Total rake is the distance from the design rotation plane to the section's mid-chord, measured positive downstream parallel to the shaft axis.

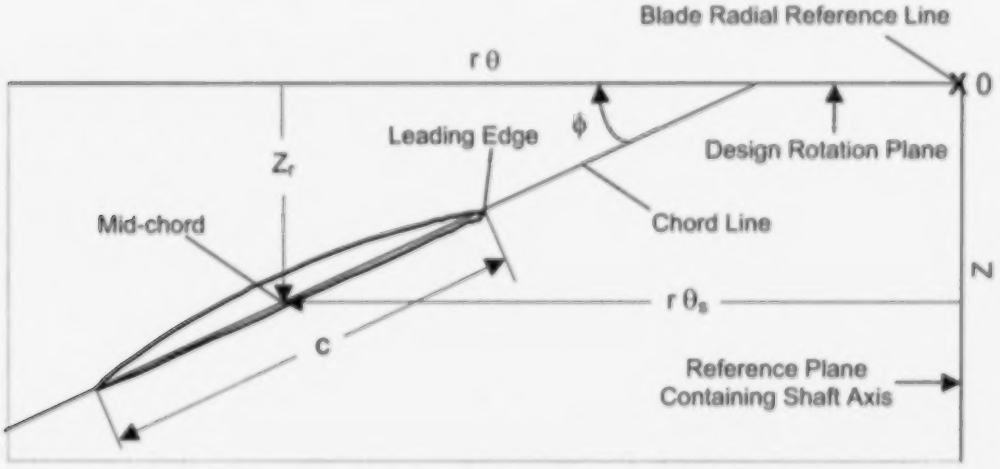


Figure 4. *Pitch Angle, Chord Length, Skew Angle and Rake of a Constant Radius Section.*

3.1.1 Section Pitch Angle

Tables 3 and 4 summarize the differences in pitch angle in degrees and percent, respectively, relative to the design pitch angle at constant radius fractions r/R of the port propeller. Positive pitch angle differences indicate sections that are over-pitched relative to design. Table 5 summarizes the largest absolute differences in pitch angle at each radius between any two blades of the port propeller both in degrees and percent relative to design.

For the port propeller, the results show that all measured sections in the outer 20 percent of the blades are over-pitched relative to the design blade. In this region, the pitch increases range from just under 0.1 degrees at r/R = 0.8 on blade 3 to 2.2 degrees at r/R = 0.975 on blade 2. In terms of percentage of design pitch, these two locations also give the minimum and maximum values of 0.3% and 11.2% over this outer region.

Sections between r/R = 0.3 and 0.75 on the port propeller are seen to vary both slightly above and below design pitch. These sections reach a maximum under-pitch of -0.6 degrees at r/R = 0.65 on blade 3 and a maximum over-pitch of 0.4 degrees at r/R = 0.75 on blade 6. As percentages of design pitch, these sections show a maximum decrease in pitch of -1.7% at r/R = 0.7 on blade 3 and a maximum increase of 1.2% at r/R=0.75 on blade 6. The root-most sections at r/R = 0.25 are all slightly over-pitched reaching a maximum of just under 0.5 degrees (0.7%) on blade 5. In Table 5, the largest inter-blade differences in pitch angle at each radius have absolute values that increase from 0.3 degrees (0.4%) between blades 3 and 5 at r/R = 0.3 to 1.4 degrees (7.1%) between blades 1 and 2 at r/R = 0.975.

Radius r/R	Blade 1	Blade 2	Blade 3	Blade 4	Blade 5	Blade 6	Blade 7
0.975	0.81	2.21	1.21	1.66	1.46	2.02	1.05
0.950	0.59	1.56	1.05	1.28	1.04	1.55	0.78
0.900	0.67	0.89	0.96	0.71	1.00	1.20	0.72
0.850	0.75	0.53	0.74	0.72	0.98	1.06	0.71
0.800	0.33	0.31	0.09	0.26	0.60	0.70	0.16
0.750	0.17	0.06	-0.32	-0.01	0.24	0.41	-0.18
0.700	-0.04	-0.15	-0.61	-0.14	-0.09	0.16	-0.36
0.650	-0.20	-0.31	-0.64	-0.35	-0.21	0.08	-0.32
0.600	-0.28	-0.34	-0.47	-0.37	-0.18	0.01	-0.23
0.500	-0.13	-0.27	-0.28	-0.54	0.00	0.07	-0.03
0.400	-0.05	-0.20	-0.18	-0.14	-0.10	0.10	0.06
0.300	-0.02	-0.05	-0.11	0.05	0.17	0.10	0.01
0.250	0.02	0.13	0.19	0.06	0.49	0.01	0.01

Table 3. *Pitch Angle Differences (in Degrees) Relative to Design for the Port Propeller.*

Radius r/R	Blade 1	Blade 2	Blade 3	Blade 4	Blade 5	Blade 6	Blade 7
0.975	4.11	11.21	6.14	8.42	7.40	10.24	5.32
0.950	2.77	7.32	4.93	6.01	4.88	7.28	3.66
0.900	2.76	3.67	3.95	2.92	4.12	4.94	2.97
0.850	2.78	1.96	2.74	2.66	3.63	3.92	2.63
0.800	1.10	1.03	0.30	0.86	1.99	2.32	0.53
0.750	0.51	0.18	-0.97	-0.03	0.73	1.24	-0.54
0.700	-0.11	-0.42	-1.69	-0.39	-0.25	0.44	-1.00
0.650	-0.51	-0.79	-1.64	-0.89	-0.54	0.20	-0.82
0.600	-0.66	-0.80	-1.11	-0.88	-0.43	0.02	-0.54
0.500	-0.27	-0.55	-0.57	-1.10	0.00	0.14	-0.06
0.400	-0.09	-0.36	-0.32	-0.25	-0.18	0.18	0.11
0.300	-0.03	-0.08	-0.17	0.08	0.27	0.16	0.02
0.250	0.03	0.20	0.29	0.09	0.74	0.02	0.02

Table 4. *Pitch Angle Differences (in Percent) Relative to Design for the Port Propeller.*

Radius r/R	Degrees	Percent	Blades
0.975	1.40	7.10	1 & 2
0.950	0.97	4.55	1 & 2
0.900	0.53	2.18	1 & 6
0.850	0.53	1.96	2 & 6
0.800	0.61	2.02	3 & 6
0.750	0.73	2.21	3 & 6
0.700	0.77	2.13	3 & 6
0.650	0.72	1.84	3 & 6
0.600	0.48	1.14	3 & 6
0.500	0.61	1.25	4 & 6
0.400	0.30	0.53	2 & 6
0.300	0.28	0.44	3 & 5
0.250	0.48	0.72	5 & 6,7

Table 5. *Maximum Inter-Blade Differences in Pitch Angle for the Port Propeller.*

Tables 6 through 8 provide the corresponding pitch angle differences for the starboard propeller. Like the port propeller, all sections in the outer 20 percent of the starboard propeller blades are again over-pitched relative to the design blade. The data in Table 8, however, show much less inter-blade variation than for the port propeller. For these outer sections, pitch increases relative to design range from less than 0.1 degrees at r/R = 0.8 on blade 1 to just over 1.8 degrees at r/R = 0.975 on blade 6. As percentages of design pitch, these same locations give minimum and maximum values of 0.1% and 9.4%.

As for the port propeller, sections between 30 and 75 percent radius vary both slightly above and below design pitch. These sections have a maximum under-pitch of -0.4 degrees at r/R = 0.4 on blade 4 and a maximum over-pitch of about 0.3 degrees at r/R = 0.75 on blade 7. As percentages of design pitch, these sections show a maximum decrease in pitch angle of –0.8% at r/R = 0.65 on blade 4 and a maximum increase of 0.8% at r/R = 0.75 on blade 7. Like the port propeller, root-most sections at r/R = 0.25 on the starboard propeller are all slightly over-pitched reaching a maximum increase of 0.4 degrees (0.6%) on blade 7.

From Table 8, the largest inter-blade differences reach an absolute value of about 0.4 degrees between various blades at seven different radii distributed from root to tip. In terms of percentages of design pitch, the inter-blade differences are largest for the outer 20% of blades and reach a maximum of 2.2% between blades 2 and 6 at r/R = 0.975.

Radius r/R	Blade 1	Blade 2	Blade 3	Blade 4	Blade 5	Blade 6	Blade 7
0.975	1.48	1.42	1.67	1.69	1.58	1.85	1.75
0.950	0.97	0.99	1.13	1.24	1.02	1.14	1.21
0.900	0.53	0.64	0.74	0.88	0.78	0.56	0.69
0.850	0.49	0.70	0.62	0.85	0.74	0.63	0.56
0.800	0.03	0.38	0.15	0.37	0.36	0.20	0.40
0.750	0.01	0.12	0.12	0.19	-0.03	-0.01	0.25
0.700	-0.27	0.05	0.08	-0.18	-0.11	-0.12	0.14
0.650	-0.27	-0.16	-0.05	-0.30	-0.17	-0.19	0.06
0.600	-0.21	-0.11	-0.18	-0.19	-0.06	-0.27	0.05
0.500	-0.10	-0.14	0.04	-0.09	0.15	-0.22	-0.04
0.400	-0.18	-0.12	-0.21	-0.38	-0.17	-0.20	-0.16
0.300	0.13	0.06	-0.07	-0.10	-0.10	0.00	-0.04
0.250	0.15	0.00	0.01	0.15	0.18	0.28	0.40

***Table 6**. Pitch Angle Differences (in Degrees) Relative to Design for the Starboard Propeller.*

Radius r/R	Blade 1	Blade 2	Blade 3	Blade 4	Blade 5	Blade 6	Blade 7
0.975	7.51	7.20	8.47	8.57	8.01	9.38	8.87
0.950	4.55	4.65	5.31	5.82	4.79	5.35	5.68
0.900	2.18	2.64	3.05	3.62	3.21	2.31	2.84
0.850	1.81	2.59	2.29	3.15	2.74	2.33	2.07
0.800	0.10	1.26	0.50	1.23	1.19	0.66	1.33
0.750	0.03	0.36	0.36	0.57	-0.09	-0.03	0.76
0.700	-0.75	0.14	0.22	-0.50	-0.30	-0.33	0.39
0.650	-0.69	-0.41	-0.13	-0.77	-0.43	-0.49	0.15
0.600	-0.50	-0.26	-0.43	-0.45	-0.14	-0.64	0.12
0.500	-0.20	-0.29	0.08	-0.18	0.31	-0.45	-0.08
0.400	-0.32	-0.21	-0.37	-0.68	-0.30	-0.36	-0.28
0.300	0.21	0.09	-0.11	-0.16	-0.16	0.00	-0.06
0.250	0.23	0.00	0.02	0.23	0.27	0.42	0.60

***Table 7**. Pitch Angle Differences (in Percent) Relative to Design for the Starboard Propeller.*

Radius r/R	Degrees	Percent	Blades
0.975	0.43	2.18	2 & 6
0.950	0.27	1.27	1 & 4
0.900	0.35	1.44	1 & 4
0.850	0.36	1.33	1 & 4
0.800	0.37	1.23	1 & 7
0.750	0.28	0.85	5 & 7
0.700	0.41	1.14	1 & 7
0.650	0.36	0.92	4 & 7
0.600	0.32	0.76	6 & 7
0.500	0.37	0.76	5 & 6
0.400	0.26	0.46	2 & 4
0.300	0.23	0.36	1 & 4,5
0.250	0.40	0.60	2 & 7

***Table 8**. Maximum Inter-Blade Differences in Pitch Angle for the Starboard Propeller.*

The previous pitch angle differences are now presented in graphical form. Figures 5a and 5b are plots of the pitch angle in degrees versus radius fraction for all measured sections on each blade of the port and starboard propellers, respectively. The radial distribution of pitch angle for the design blade is also plotted on these figures using a dashed line. Figures 5c and 5d provide a close-up view of these results over the outer 20% of blades where the pitch angle differences are largest.

Figures 5a and 5c show a wide range of pitch angle increases relative to design approaching the tips of each blade of the port propeller. This inter-blade variation should produce a wide range of cavitation inception speeds in the tip region of port propeller blades. Blade 2 with the largest increase in pitch angle should have the largest decrease in inception speed in this area on the back surface. Figures 5b and 5d show the pitch angles of each blade of the starboard propeller to be very close at all radii but still increasing significantly relative to design approaching the tips. All of these blades should have similarly large decreases in inception speeds of back surface cavitation in the tip region relative to the design blade.

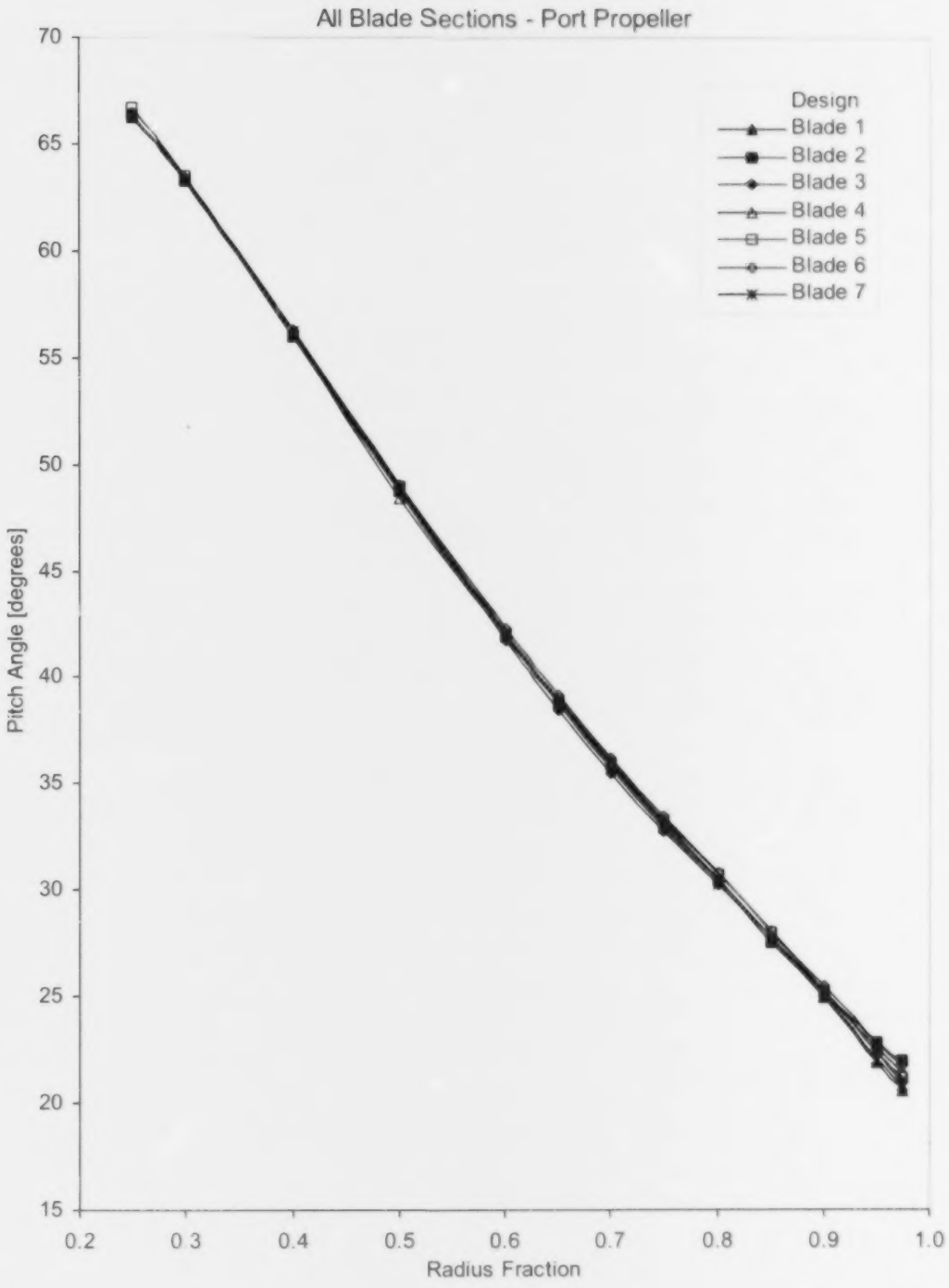


Figure 5a. *Radial Pitch Distribution for All Blade Sections of the Port Propeller.*

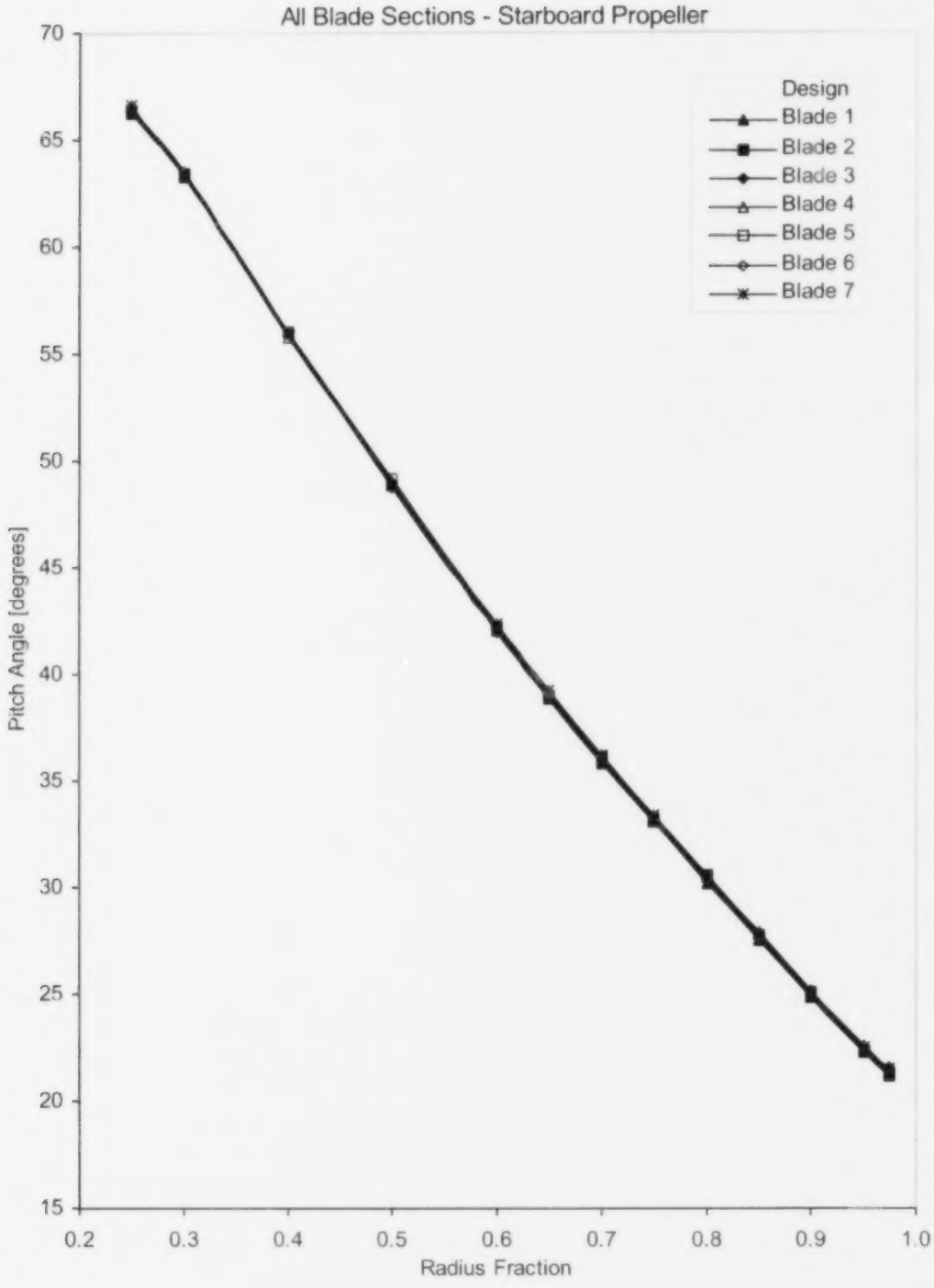


Figure 5b. *Radial Pitch Distribution for All Blade Sections of the Starboard Propeller.*

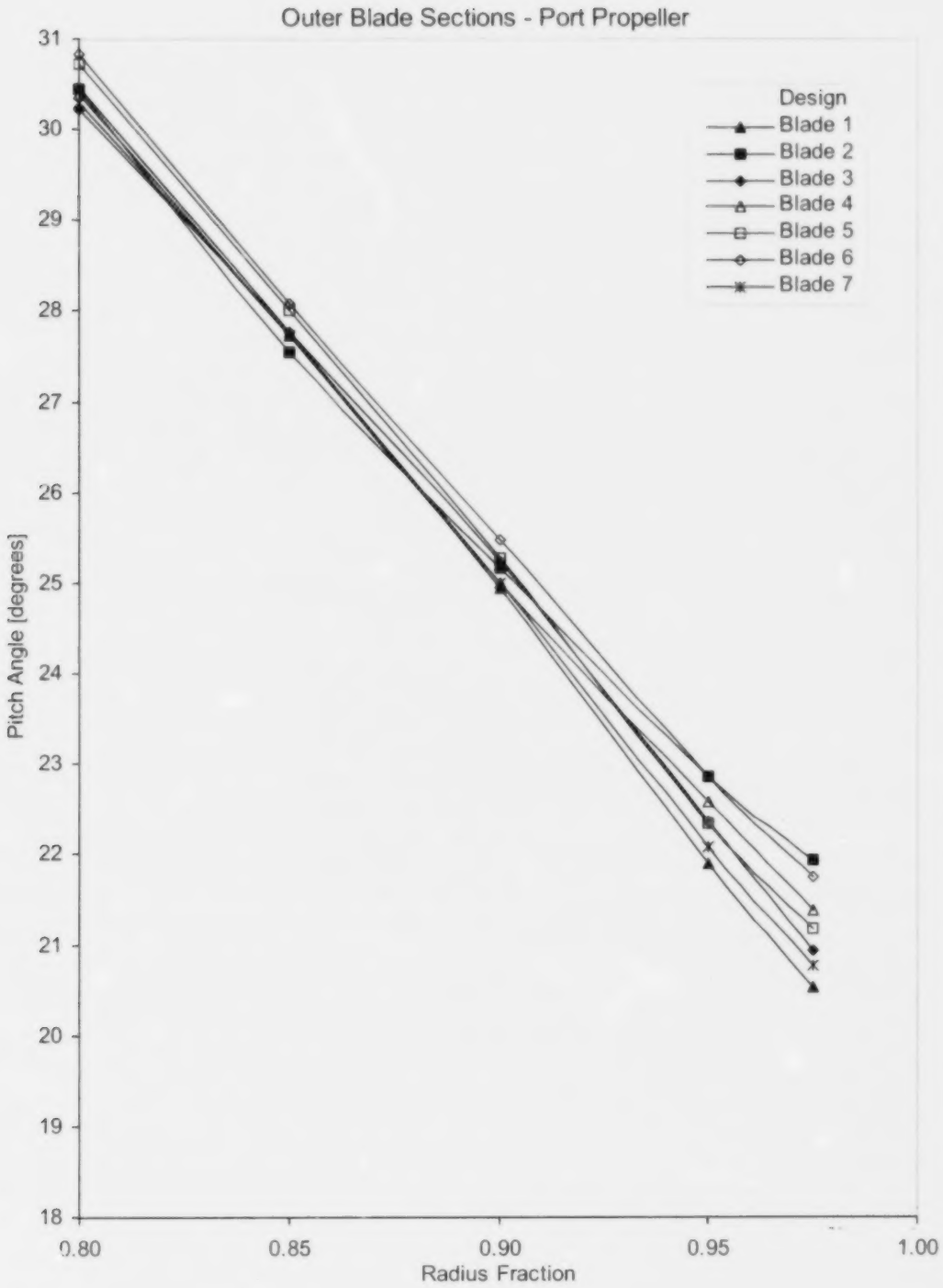


Figure 5c. *Radial Pitch Distribution for Outer Blade Sections of the Port Propeller.*

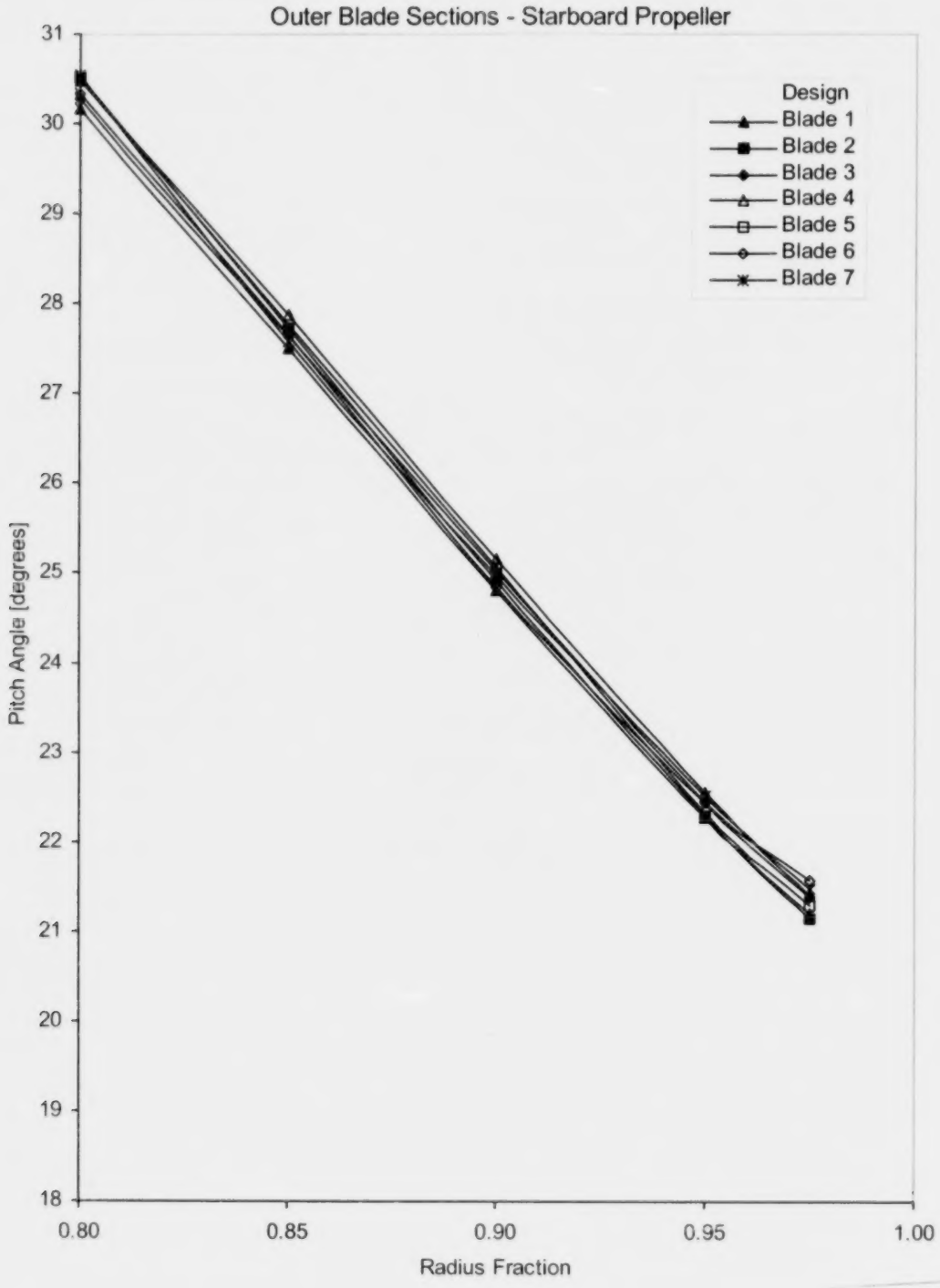


Figure 5d. *Radial Pitch Distribution for Outer Blade Sections of the Starboard Propeller.*

3.1.2 Section Chord Length

Tables 9 and 10 summarize the differences in chord length in millimetres and percent, respectively, relative to the design chord length at constant radius fractions r/R of the port propeller. Positive chord length differences indicate sections with chord lengths greater than design values. Table 11 summarizes the largest absolute differences in chord length between blades at each radius of the port propeller both in millimetres and percent relative to design.

For the port propeller, the measurements show smaller chord lengths relative to design for all sections except for r/R = 0.975 on six blades and r/R = 0.3 on blade 2. Except for blade 6, the tip-most section has increases in chord length that range from 14.1 mm (2.5% of design chord length) on blade 4 to 31.6 mm (5.6%) on blade 5. On blade 6, the outer-most section has a decrease in chord length of -12.2 mm (-2.1%). On blade 2, the section chord length at 30 percent radius has a slight increase of about 0.5 mm (less than 0.1%). Apart from the tip-most radius, the outer 20% of blades have decreases in chord length that range from -5.9 mm (-0.5%) at r/R = 0.9 on blade 1 to -45.6 mm (-5.5%) at r/R = 0.95 on blade 6. Sections at radii below r/R = 0.8 have decreases in chord length ranging from -0.3 mm (less than -0.1%) at r/R = 0.3 on blade 1 to -16.8 mm (-1.2%) at r/R = 0.60 on blade 3.

As can be seen from Table 11, the largest inter-blade differences in chord length at each radius of the port propeller have absolute values that increase from 4.4 mm (0.4%) between blades 2 and 6 at r/R = 0.4 to 43.8 mm (7.7%) between blades 5 and 6 at r/R = 0.975. The large variations in chord length on outer radius blade sections are largely responsible for the significant inter-blade differences in the shapes of the outer edge outlines observed during the brief inspection prior to the sea trial. These variations are not likely to affect the inception speed of cavitation at the tip in any significant way.

Radius r/R	Blade 1	Blade 2	Blade 3	Blade 4	Blade 5	Blade 6	Blade 7
0.975	22.98	16.26	24.53	14.07	31.65	-12.16	26.97
0.950	-9.02	-15.34	-21.38	-29.03	-21.40	-45.60	-16.91
0.900	-5.93	-15.62	-20.79	-20.13	-20.47	-12.84	-8.37
0.850	-13.27	-18.55	-16.20	-19.22	-16.30	-12.60	-13.68
0.800	-9.90	-12.85	-10.33	-10.91	-6.35	-10.39	-6.73
0.750	-7.39	-6.34	-1.79	-7.55	-6.33	-8.89	-2.17
0.700	-7.47	-6.75	-2.03	-6.53	-3.18	-3.83	-5.38
0.650	-7.73	-9.84	-6.44	-5.83	-5.44	-9.61	-12.55
0.600	-8.11	-11.80	-16.76	-10.02	-5.98	-9.20	-14.09
0.500	-3.88	-4.95	-11.92	-7.02	-5.26	-7.97	-8.18
0.400	-2.71	-0.37	-1.98	-2.81	-1.85	-4.82	-3.85
0.300	-0.34	0.54	-4.96	-2.13	-0.53	-2.85	-1.45
0.250	-8.00	-4.50	-8.09	-6.59	-2.56	-4.39	-8.15

***Table 9**. Chord Length Differences (in Millimetres) Relative to D ign for the Port Propeller.*

Radius r/R	Blade 1	Blade 2	Blade 3	Blade 4	Blade 5	Blade 6	Blade 7
0.975	4.07	2.88	4.34	2.49	5.60	-2.15	4.77
0.950	-1.09	-1.85	-2.58	-3.50	-2.58	-5.49	-2.04
0.900	-0.54	-1.43	-1.90	-1.84	-1.87	-1.17	-0.76
0.850	-1.08	-1.51	-1.32	-1.56	-1.32	-1.02	-1.11
0.800	-0.76	-0.98	-0.79	-0.83	-0.49	-0.79	-0.51
0.750	-0.55	-0.47	-0.13	-0.56	-0.47	-0.66	-0.16
0.700	-0.54	-0.49	-0.15	-0.47	-0.23	-0.28	-0.39
0.650	-0.56	-0.72	-0.47	-0.42	-0.40	-0.70	-0.91
0.600	-0.61	-0.88	-1.25	-0.75	-0.45	-0.69	-1.05
0.500	-0.32	-0.41	-0.99	-0.58	-0.44	-0.66	-0.68
0.400	-0.26	-0.04	-0.19	-0.27	-0.18	-0.47	-0.38
0.300	-0.04	0.06	-0.58	-0.25	-0.06	-0.33	-0.17
0.250	-1.04	-0.58	-1.05	-0.86	-0.33	-0.57	-1.06

***Table 10**. Chord Length Differences (in Percent) Relative to Design for the Port Propeller.*

Radius r/R	Millimetres	Percent	Blades
0.975	43.81	7.75	5 & 6
0.950	36.58	4.41	1 & 6
0.900	14.86	1.36	1 & 3
0.850	6.62	0.54	4 & 6
0.800	6.50	0.50	2 & 5
0.750	7.10	0.52	3 & 6
0.700	5.44	0.40	1 & 3
0.650	7.11	0.52	5 & 7
0.600	10.78	0.80	3 & 5
0.500	8.04	0.67	1 & 3
0.400	4.45	0.43	2 & 6
0.300	5.50	0.64	2 & 3
0.250	5.59	0.73	5 & 7

***Table 11**. Maximum Inter-Blade Differences in Chord Length for the Port Propeller.*

Tables 12 through 14 provide the corresponding chord length differences for the starboard propeller. All blades have the largest increases in chord length relative to design occurring on the tip-most section at r/R = 0.975. The tip-most section has increases ranging from 44.4 mm (7.9%) on blade 5 to 62.1 mm (11.0%) on blade 2. These are much larger than the tip increases obtained on the port propeller. For all other sections, chord length variations range from a maximum decrease in chord length of about -19.0 mm (-1.5%) at 85 percent radius on blades 1 and 5 to a maximum increase of 14.3 mm (1.7%) at 95 percent radius on blade 2.

As shown in Table 14, the largest inter-blade differences in chord length at each radius of the starboard propeller have absolute values increasing from 6.6 mm (0.5%) between blades 3 and 6 at r/R = 0.6 to 24.1 mm (2.9%) between blades 1 and 2 at r/R = 0.95. The variations in chord length between blades approaching the tip are much smaller than on the port propeller.

Radius r/R	Blade 1	Blade 2	Blade 3	Blade 4	Blade 5	Blade 6	Blade 7
0.975	50.07	62.07	60.05	54.03	44.38	48.55	51.23
0.950	-9.78	14.33	12.21	9.85	-9.51	0.19	-5.40
0.900	-12.97	2.55	-8.21	-1.13	-16.59	-9.76	-8.67
0.850	-18.97	-5.40	-17.53	-14.95	-18.98	-11.76	-7.00
0.800	-5.74	-1.10	1.25	-1.18	-4.03	-0.74	-0.87
0.750	-1.98	5.08	5.02	6.03	10.50	5.60	-0.83
0.700	3.83	9.29	9.87	7.87	9.16	8.90	0.84
0.650	3.21	10.08	9.91	2.59	4.98	4.63	4.68
0.600	5.10	4.96	5.73	0.97	1.28	-0.83	1.32
0.500	1.25	0.44	-1.98	3.85	-1.52	-6.04	2.67
0.400	2.19	-4.36	-0.57	1.17	2.46	-2.30	0.79
0.300	0.09	-9.94	-3.99	-10.54	-0.92	-3.73	-4.98
0.250	-5.77	-10.24	-8.26	-13.20	-4.70	-10.81	-3.66

***Table 12**. Chord Length Differences (in Millimetres) Relative to Design for the Starboard Propeller.*

Radius r/R	Blade 1	Blade 2	Blade 3	Blade 4	Blade 5	Blade 6	Blade 7
0.975	8.86	10.99	10.63	9.56	7.86	8.59	9.07
0.950	-1.18	1.73	1.47	1.19	-1.15	0.02	-0.65
0.900	-1.18	0.23	-0.75	-0.10	-1.51	-0.89	-0.79
0.850	-1.54	-0.44	-1.42	-1.22	-1.54	-0.96	-0.57
0.800	-0.44	-0.08	0.10	-0.09	-0.31	-0.06	-0.07
0.750	-0.15	0.38	0.37	0.45	0.78	0.41	-0.06
0.700	0.28	0.68	0.72	0.57	0.67	0.65	0.06
0.650	0.23	0.73	0.72	0.19	0.36	0.34	0.34
0.600	0.38	0.37	0.43	0.07	0.10	-0.06	0.10
0.500	0.10	0.04	-0.16	0.32	-0.13	-0.50	0.22
0.400	0.21	-0.43	-0.06	0.11	0.24	-0.22	0.08
0.300	0.01	-1.16	-0.47	-1.23	-0.11	-0.44	-0.58
0.250	-0.75	-1.33	-1.07	-1.72	-0.61	-1.40	-0.48

Table 13. *Chord Length Differences (in Percent) Relative to Design for the Starboard Propeller.*

Radius r/R	Millimeters	Percent	Blades
0.975	17.69	3.13	2 & 5
0.950	24.11	2.91	1 & 2
0.900	19.14	1.75	2 & 5
0.850	13.58	1.10	2 & 5
0.800	6.99	0.53	1 & 3
0.750	12.48	0.92	1 & 5
0.700	9.03	0.66	3 & 7
0.650	7.49	0.55	2 & 4
0.600	6.56	0.49	3 & 6
0.500	9.89	0.82	4 & 6
0.400	6.82	0.67	2 & 5
0.300	10.63	1.24	1 & 4
0.250	9.54	1.24	4 & 7

Table 14. *Maximum Inter-Blade Differences in Chord Length for the Starboard Propeller.*

The previous chord length differences are now presented in graphical form. Figures 6a and 6b are plots of the chord length versus radius fraction for the port and starboard propellers, respectively. The radial distribution of chord length for the design blade is also shown using a dashed line. Figures 6c and 6d provide a close-up view of these results for the three outermost measured blade sections.

Figure 6c shows a wide range of chord length differences relative to design approaching the tips of port propeller blades. Figure 6d shows much less inter-blade variation for the starboard propeller but much larger increases in chord length approaching the tips. This results in significant visible differences in the tip shapes of port propeller blades compared to starboard propeller blades. These differences in chord length should not influence cavitation performance significantly.

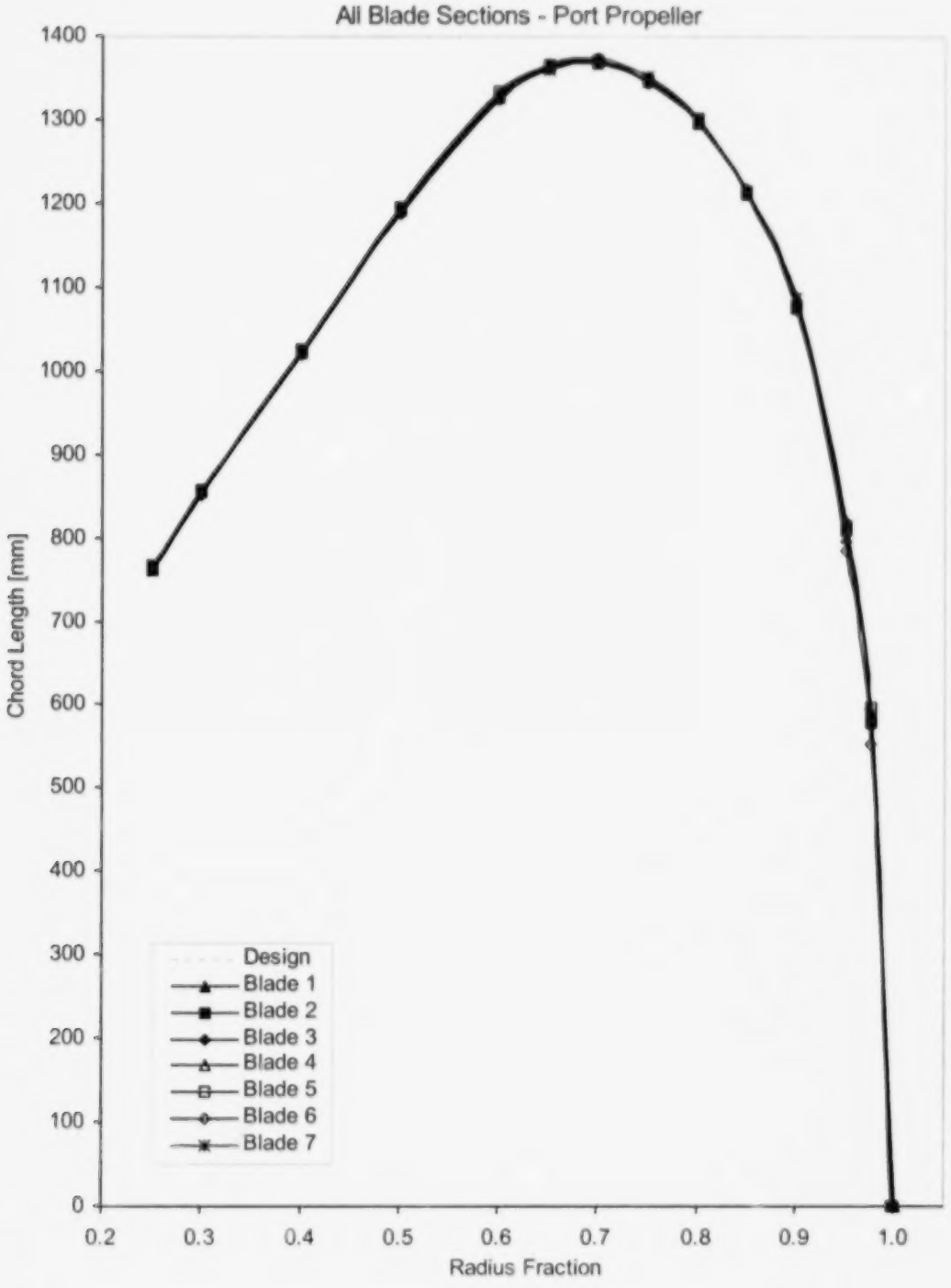


Figure 6a. *Radial Chord Distribution for All Blade Sections of the Port Propeller.*

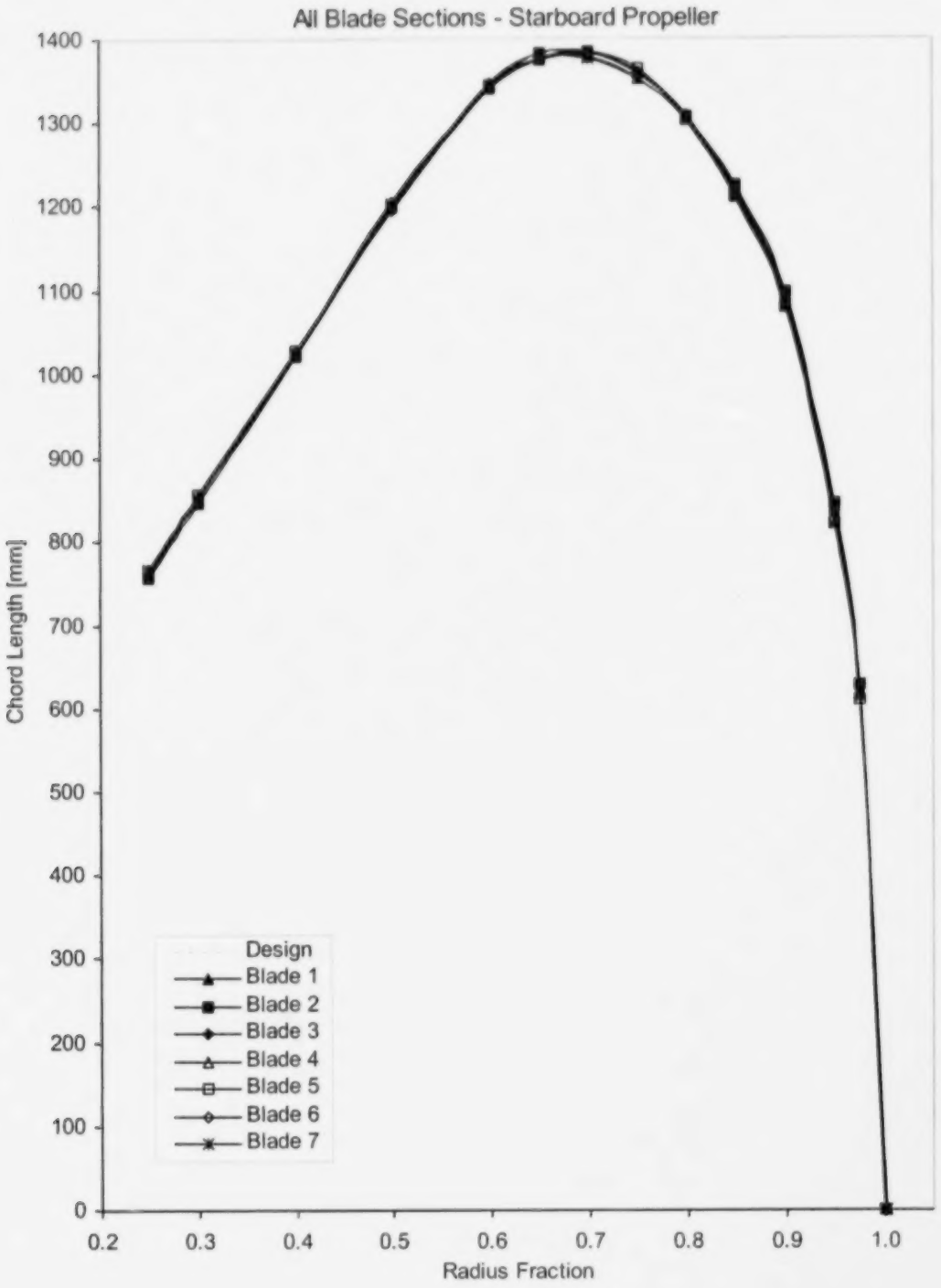


Figure 6b. *Radial Chord Distribution for All Blade Sections of the Starboard Propeller.*

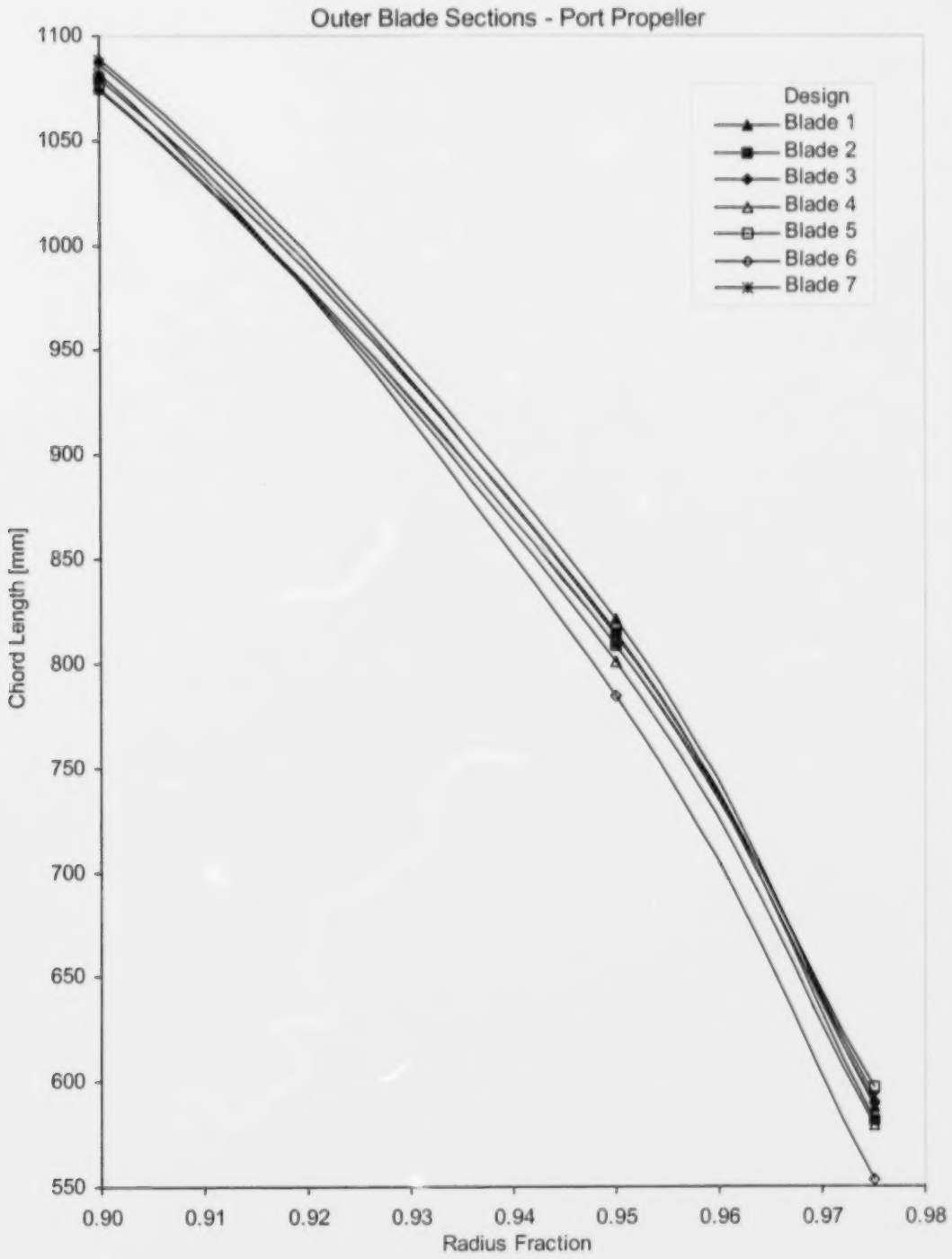


Figure 6c. *Radial Chord Distribution for Outer Blade Sections of the Port Propeller.*

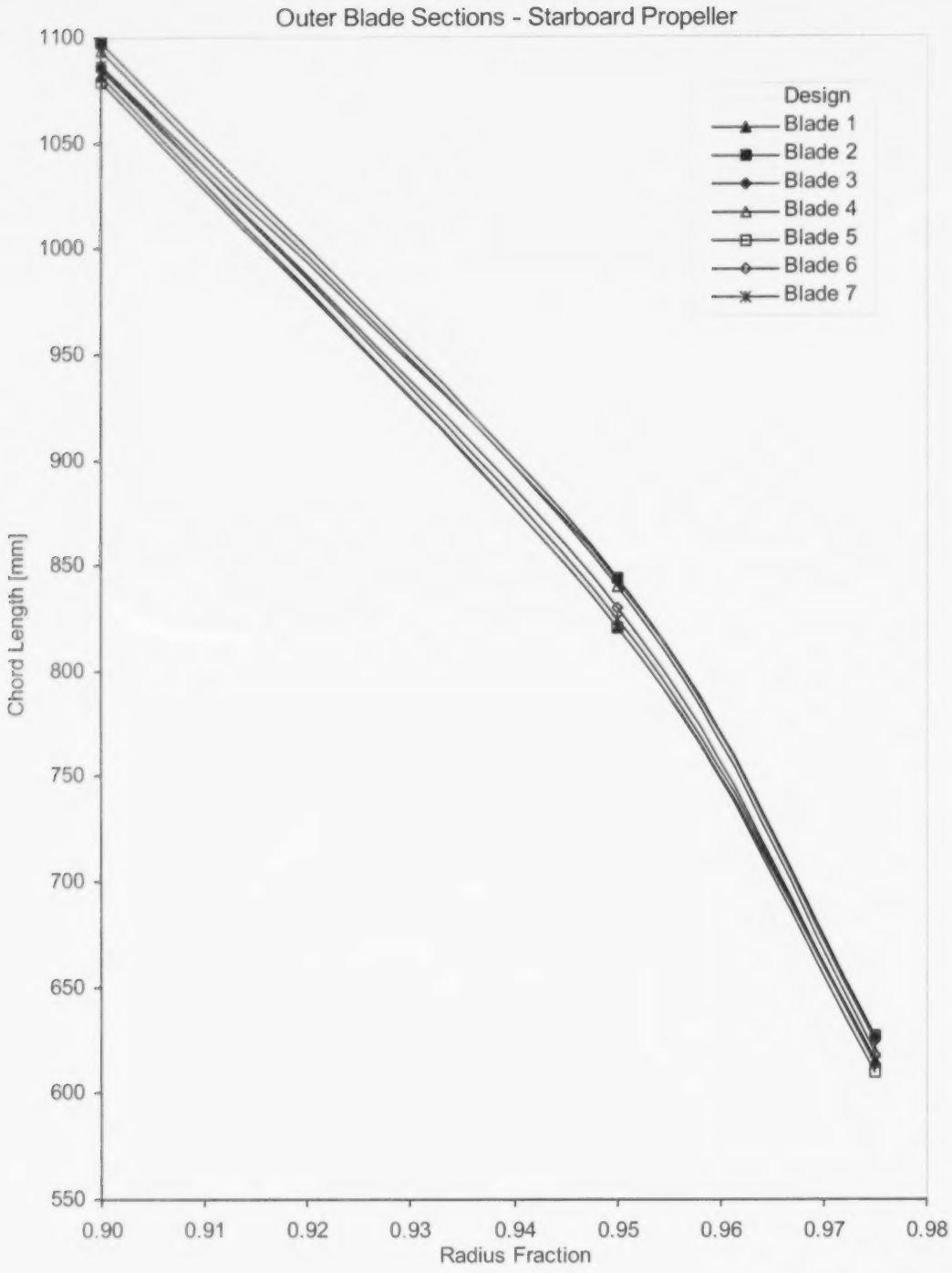


Figure 6d. *Radial Chord Distribution for Outer Blade Sections of the Starboard Propeller.*

3.1.3 Section Skew Angle

To compare the relative radial distribution of section skew angles for each blade to the design distribution, the angular coordinates of surface points on each blade were rotated until their root-most leading edge angle was matched to that of the design blade at its reference position. This essentially removed inter-blade spacing differences from the comparison. The skew angle of mid-chord points was then defined as the mean of the rotated leading and trailing edge angles.

Tables 15 and 16 summarize the differences in skew angle in degrees and percent, respectively, relative to the design skew angle at constant radius fractions r/R of the port propeller. Positive skew angle differences indicate sections that are over-skewed or have mid-chord points at a larger rotation plane angle downstream from the blade's radial reference line relative to design. Table 17 summarizes the largest absolute differences in skew angles between blades at each radius both in degrees and percent for the port propeller.

For the port propeller, the results show that all mid-chord points are slightly under-skewed relative to the design blade except for the tip on blade 6. Blade 6 is over-skewed by 0.8 degrees (4.1%) on the tip-most section. The absolute differences in skew angle in degrees are all less than one degree relative to design except for the tip on blade 4 where a skew decrease of -1.7 degrees (-9.0%) is measured. In general, the largest skew differences in degrees are on the outer radius sections of each blade. The percentage differences in Table 16 are seen to increase rapidly with decreasing radius below 70% of the tip radius due to division by the rapidly decreasing skew angle of the design blade, even though the absolute differences in degrees for this region never exceed 0.9. From Table 17, the largest inter-blade differences in degrees at each radius of the port propeller have absolute values that increase from 0.2 degrees between blades 1 or 6 and 2 at r/R = 0.95 to 2.5 degrees between the tips of blades 4 and 6.

Radius r/R	Blade 1	Blade 2	Blade 3	Blade 4	Blade 5	Blade 6	Blade 7
1.000	-0.61	-0.91	-0.81	-1.71	-0.61	0.79	-0.41
0.975	-0.69	-0.79	-0.69	-0.89	-0.59	-0.04	-0.64
0.950	-0.43	-0.63	-0.58	-0.53	-0.48	-0.43	-0.48
0.900	-0.45	-0.85	-0.56	-0.60	-0.35	-0.36	-0.50
0.850	-0.21	-0.76	-0.46	-0.71	-0.41	-0.36	-0.51
0.800	-0.39	-0.64	-0.54	-0.49	-0.29	-0.39	-0.49
0.750	-0.54	-0.59	-0.49	-0.49	-0.24	-0.34	-0.44
0.700	-0.46	-0.61	-0.46	-0.41	-0.36	-0.37	-0.41
0.650	-0.42	-0.62	-0.42	-0.52	-0.37	-0.27	-0.37
0.600	-0.35	-0.50	-0.35	-0.45	-0.25	-0.30	-0.50
0.500	-0.42	-0.47	-0.22	-0.37	-0.32	-0.42	-0.57
0.400	-0.12	-0.37	-0.12	-0.37	-0.27	-0.27	-0.52
0.300	-0.44	-0.89	-0.49	-0.64	-0.19	-0.29	-0.39
0.250	-0.23	-0.23	-0.38	-0.23	-0.48	-0.13	-0.23

***Table 15**. Skew Angle Differences (in Degrees) Relative to Design for the Port Propeller.*

Radius r/R	Blade 1	Blade 2	Blade 3	Blade 4	Blade 5	Blade 6	Blade 7
1.000	-3.22	-4.80	-4.27	-9.01	-3.22	4.15	-2.17
0.975	-3.89	-4.46	-3.89	-5.02	-3.33	-0.23	-3.61
0.950	-2.58	-3.79	-3.49	-3.18	-2.88	-2.58	-2.88
0.900	-3.21	-6.02	-3.91	-4.26	-2.50	-2.50	-3.56
0.850	-1.71	-6.28	-3.79	-5.87	-3.38	-2.96	-4.21
0.800	-3.83	-6.31	-5.32	-4.82	-2.84	-3.83	-4.82
0.750	-6.49	-7.09	-5.89	-5.89	-2.86	-4.07	-5.28
0.700	-6.99	-9.25	-6.99	-6.24	-5.49	-5.49	-6.24
0.650	-8.12	-11.96	-8.12	-10.04	-7.16	-5.24	-7.16
0.600	-8.96	-12.77	-8.96	-11.50	-6.42	-7.69	-12.77
0.500	-21.84	-24.47	-11.33	-19.21	-16.58	-21.84	-29.72
0.400	-22.17	-66.70	-22.17	-66.70	-48.89	-48.89	-93.41
0.300	-648.91	-1305.84	-721.90	-940.88	-283.94	-429.93	-575.91
0.250	-175.00	-175.00	-288.64	-175.00	-364.39	-99.24	-175.00

***Table 16**. Skew Angle Differences (in Percent) Relative to Design for the Port Propeller.*

Radius r/R	Degrees	Percent	Blades
1.000	2.50	13.16	4 & 6
0.975	0.85	4.79	4 & 6
0.950	0.20	1.21	1,6 & 2
0.900	0.50	3.52	2 & 5
0.850	0.55	4.57	1 & 2
0.800	0.35	3.47	2 & 5
0.750	0.35	4.23	2 & 5
0.700	0.25	3.76	2 & 5
0.650	0.35	6.72	2 & 6
0.600	0.25	6.35	2,7 & 5
0.500	0.35	18.40	3 & 7
0.400	0.40	71.24	1,3 & 7
0.300	0.70	1021.90	2 & 5
0.250	0.35	265.15	5 & 6

***Table 17**. Maximum Inter-Blade Differences in Skew Angle for the Port Propeller.*

Tables 18 through 20 provide the corresponding differences for the starboard propeller. This propeller has more sections that are over-skewed relative to design than the port propeller, but the absolute inter-blade differences in degrees are less. The absolute skew angle differences in degrees are all within 0.9 degrees of design values, even for the blade tips. The largest decrease in skew angle of -0.5 degrees occurs at r/R = 0.25 on blade 6 while the largest increase of 0.9 degrees occurs at r/R = 0.6 on blade 4. As for the port propeller, the percentage differences increase rapidly as the blade roots are approached due to design skew angles approaching zero. From Table 20, the absolute inter-blade differences in degrees range from 0.3 degrees between blades 3 and 6 at the root to 1.25 degrees between blades 3 and 5 at r/R = 0.975.

Radius r/R	Blade 1	Blade 2	Blade 3	Blade 4	Blade 5	Blade 6	Blade 7
1.000	-0.21	0.79	0.59	0.59	0.19	0.19	0.09
0.975	-0.09	0.41	0.76	0.36	-0.49	-0.34	-0.09
0.950	-0.08	0.52	0.67	0.42	-0.48	-0.13	-0.13
0.900	0.04	0.50	0.50	0.69	-0.15	-0.10	0.09
0.850	0.14	0.44	0.64	0.84	-0.01	-0.06	0.04
0.800	0.16	0.26	0.66	0.76	0.01	0.01	-0.14
0.750	0.31	0.31	0.61	0.61	0.36	0.06	-0.04
0.700	0.43	0.44	0.74	0.78	0.39	0.19	0.03
0.650	0.53	0.43	0.68	0.83	0.33	0.13	-0.07
0.600	0.50	0.45	0.80	0.90	0.25	0.10	0.00
0.500	0.48	0.28	0.63	0.83	-0.02	0.08	-0.02
0.400	0.38	-0.02	0.63	0.78	-0.02	0.18	0.23
0.300	0.06	-0.24	0.11	0.16	-0.09	-0.24	-0.04
0.250	-0.28	-0.28	-0.23	-0.48	-0.28	-0.53	-0.43

***Table 18**. Skew Angle Differences (in Degrees) Relative to Design for the Starboard Propeller.*

Radius r/R	Blade 1	Blade 2	Blade 3	Blade 4	Blade 5	Blade 6	Blade 7
1.000	-1.12	4.15	3.09	3.09	0.99	0.99	0.46
0.975	-0.51	2.31	4.29	2.03	-2.76	-1.92	-0.51
0.950	-0.46	3.18	4.08	2.57	-2.88	-0.76	-0.76
0.900	0.32	3.49	3.49	4.90	-1.09	-0.74	0.67
0.850	1.19	3.68	5.34	7.00	-0.05	-0.47	0.36
0.800	1.63	2.62	6.59	7.58	0.14	0.14	-1.35
0.750	3.78	3.78	7.41	7.41	4.39	0.76	-0.45
0.700	6.54	6.54	11.05	11.80	5.79	2.78	0.53
0.650	10.12	8.20	12.99	15.87	6.28	2.44	-1.40
0.600	12.61	11.35	20.23	22.77	6.27	2.46	-0.08
0.500	25.47	14.95	33.35	43.86	-0.81	4.44	-0.81
0.400	66.87	-4.36	111.40	138.11	-4.36	31.26	40.16
0.300	81.02	-356.93	154.01	227.01	-137.96	-356.93	-64.96
0.250	-212.88	-212.88	-175.00	-364.39	-212.88	-402.27	-326.52

***Table 19**. Skew Angle Differences (in Percent) Relative to Design for the Starboard Propeller.*

Radius r/R	Degrees	Percent	Blades
1.000	1.00	5.26	1 & 2
0.975	1.25	7.05	3 & 5
0.950	1.15	6.96	3 & 5
0.900	0.84	5.92	4 & 5
0.850	0.90	7.47	4 & 6
0.800	0.90	8.93	4 & 7
0.750	0.65	7.86	3,4 & 7
0.700	0.75	11.27	4 & 7
0.650	0.90	17.27	4 & 7
0.600	0.90	22.84	4 & 7
0.500	0.85	44.68	4 & 5,7
0.400	0.80	142.48	2,5 & 4
0.300	0.40	583.94	2,6 & 4
0.250	0.30	227.27	3 & 6

***Table 20**. Maximum Inter-Blade Differences in Skew Angle for the Starboard Propeller.*

Figures 7a and 7b are plots of the skew angle versus radius fraction for all measured sections on the port and starboard propellers, respectively. The radial distribution of skew angle for the design blade is also plotted using a dashed line. Figures 7c and 7d provide a closer look at these results over the outer 25% of blades. A comparison of Figures 7c and 7d shows the much larger inter-blade variation in skew angle approaching the tips of port propeller blades relative to starboard blades.

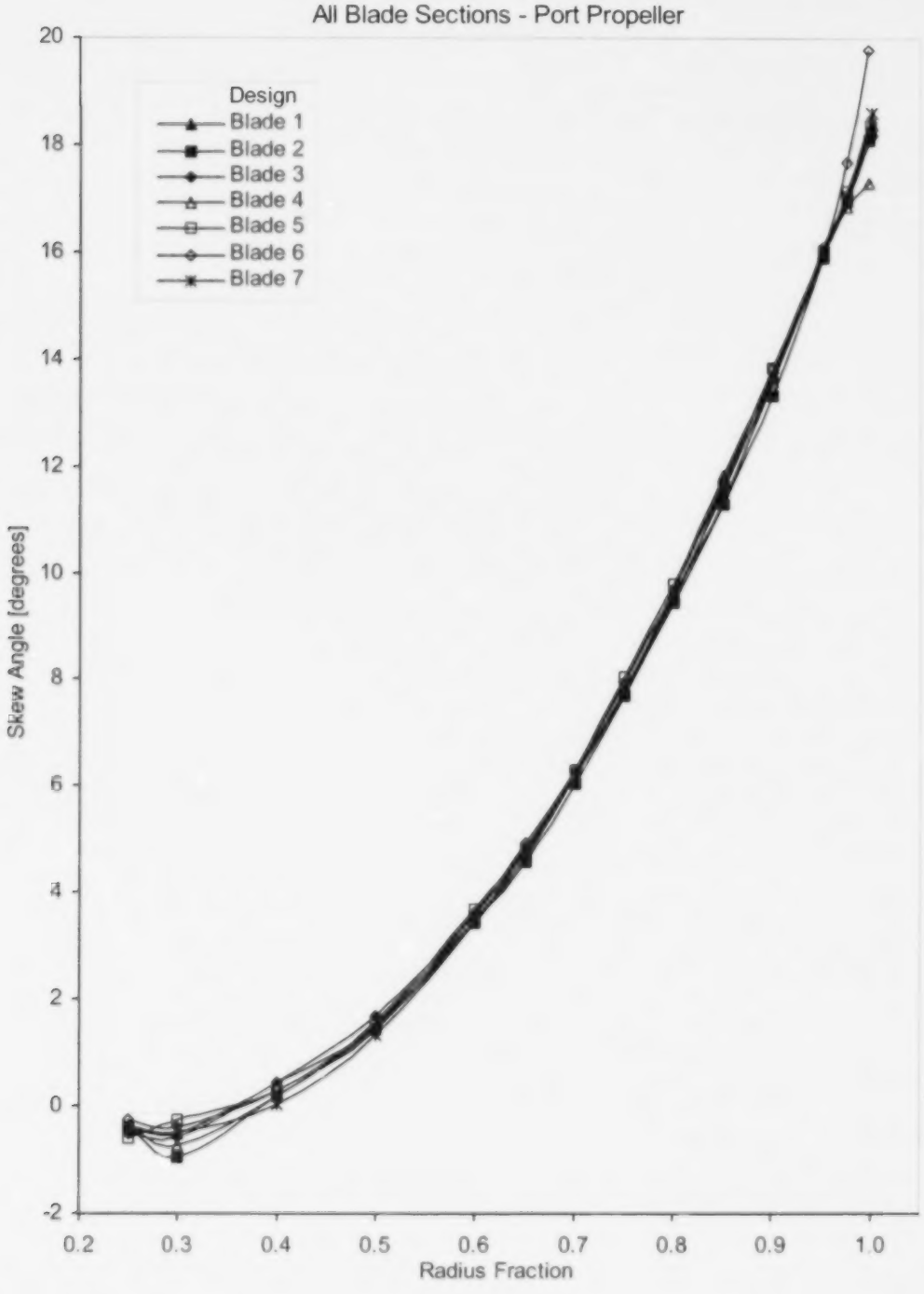


Figure 7a. *Radial Skew Distribution for All Blade Sections of the Port Propeller.*

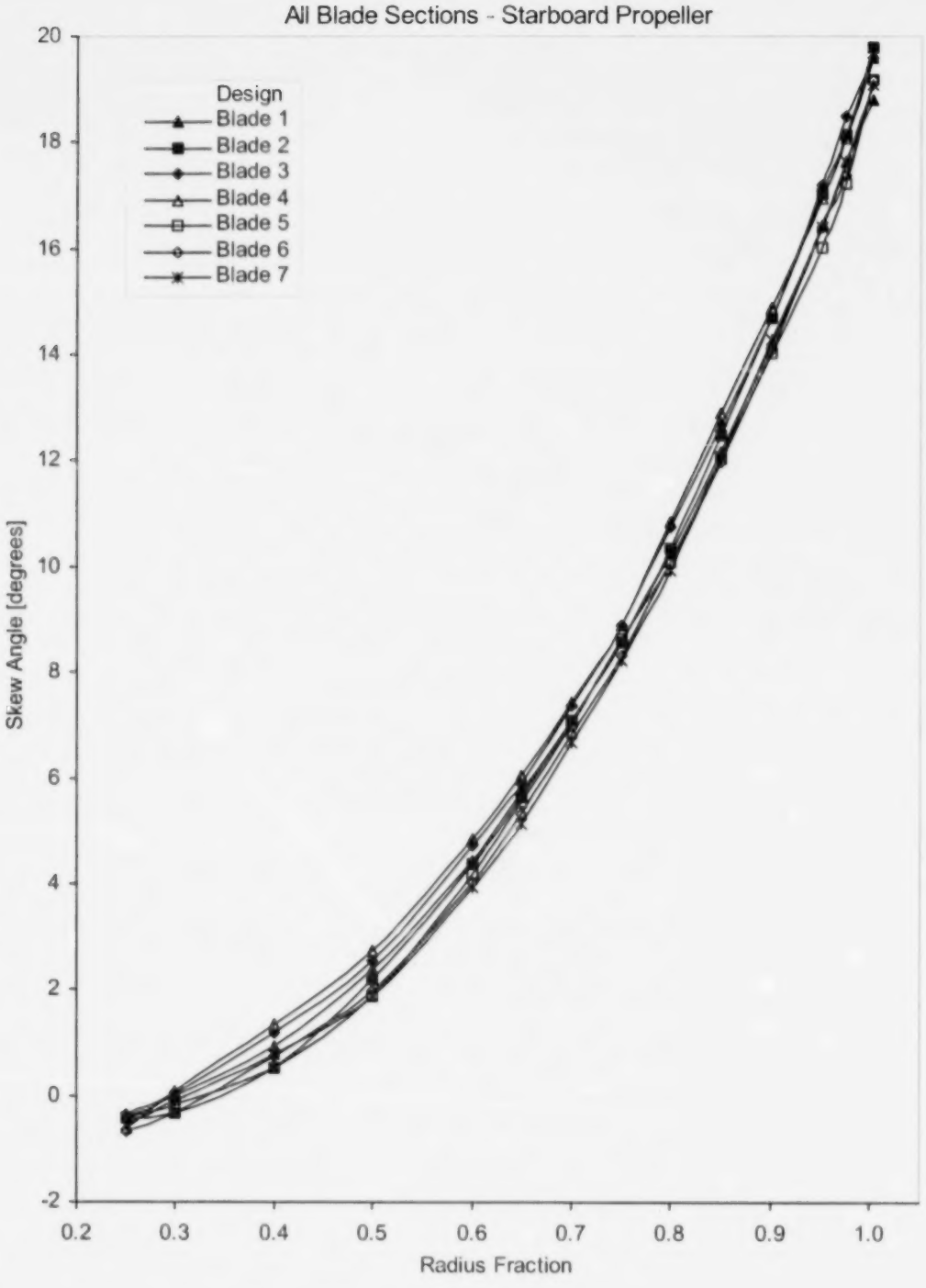


Figure 7b. *Radial Skew Distribution for All Blade Sections of the Starboard Propeller.*

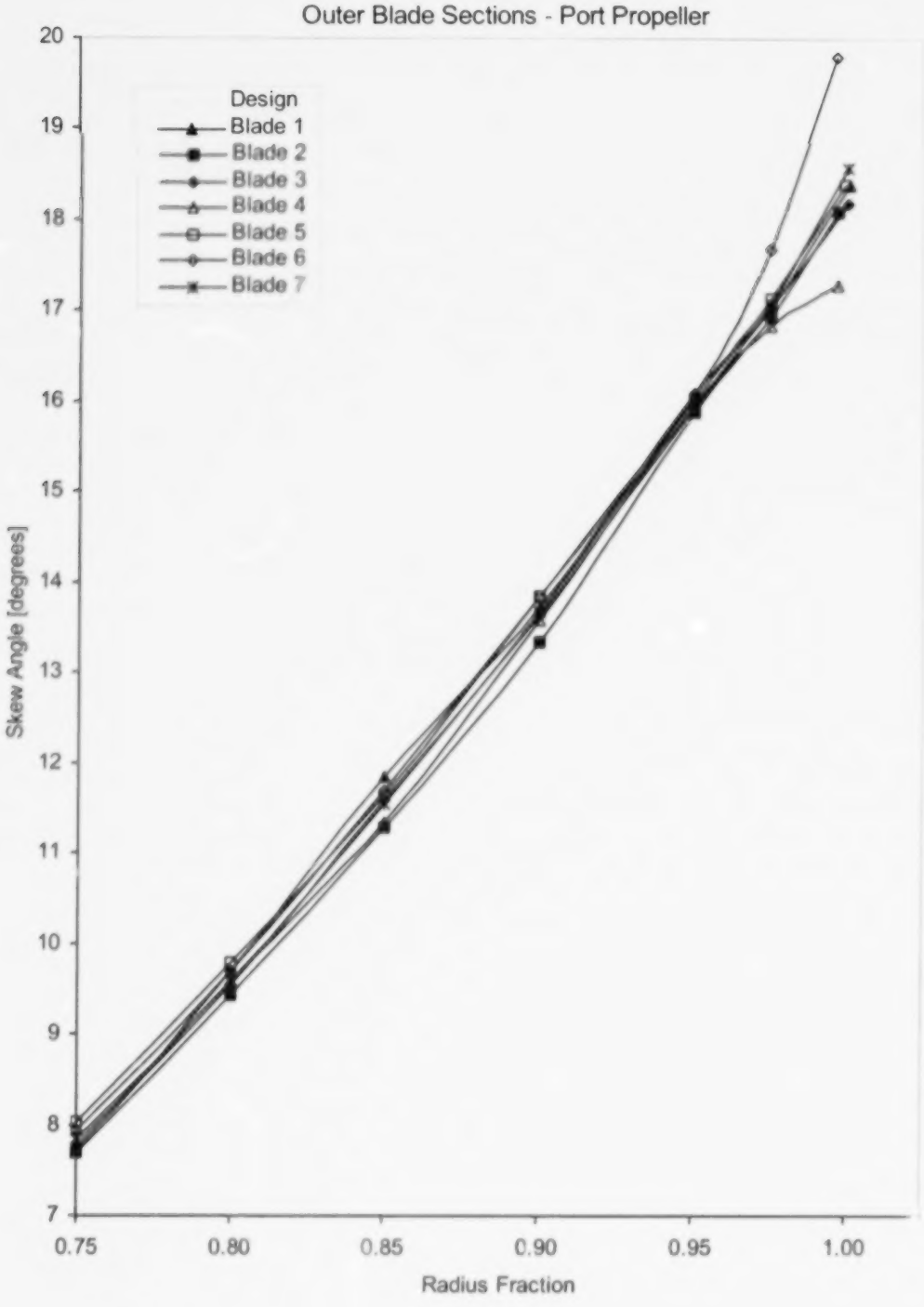


Figure 7c. *Radial Skew Distribution for Outer Blade Sections of the Port Propeller.*

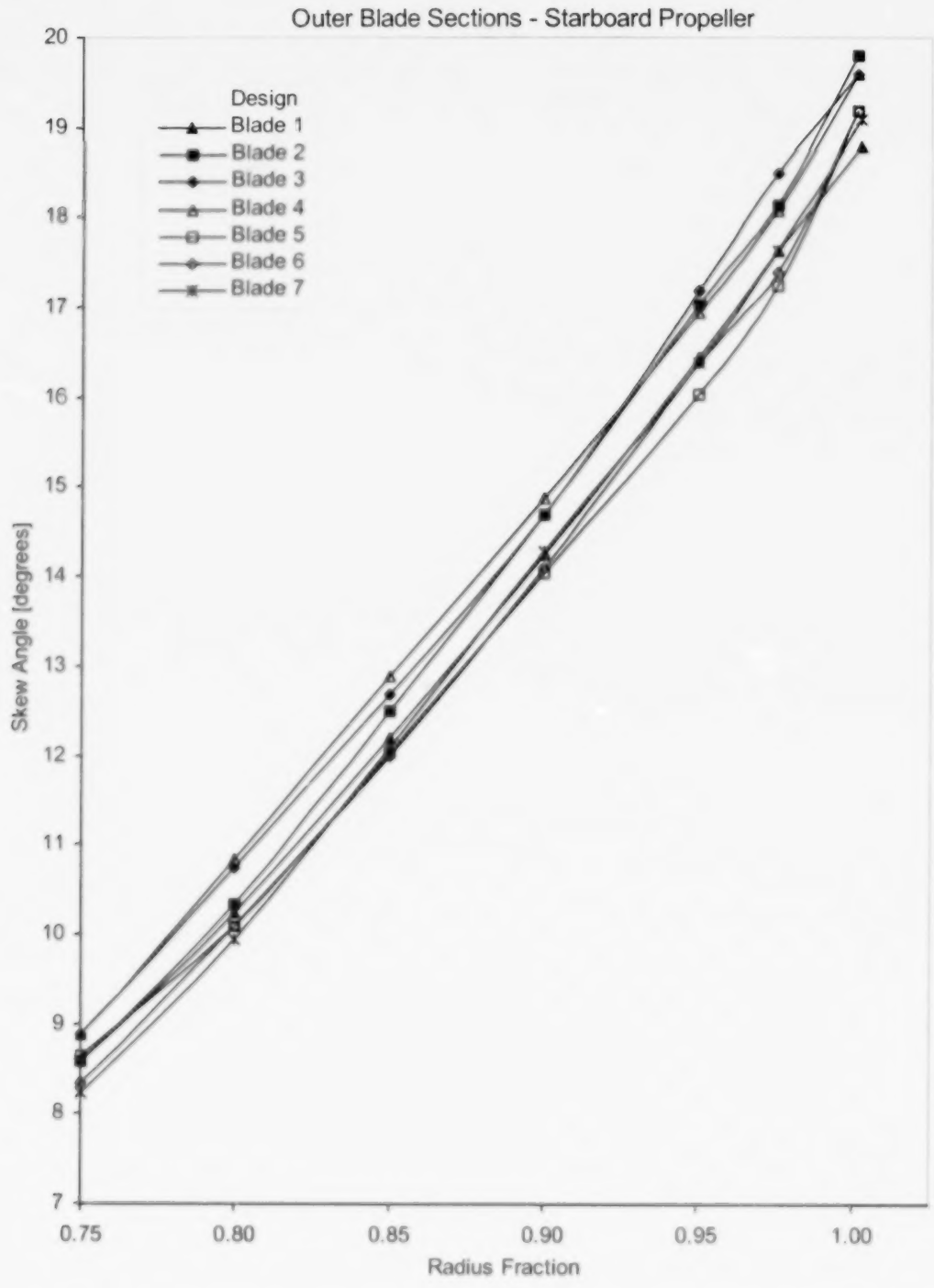


Figure 7d. *Radial Skew Distribution for Outer Blade Sections of the Starboard Propeller.*

3.1.4 Section Total Rake

Tables 21 and 22 summarize the differences in total rake in millimetres and percent, respectively, relative to the total design rake at constant radius fractions r/R of the port propeller. Positive rake differences indicate sections that are over-raked or displaced further downstream axially relative to design. Table 23 summarizes the largest absolute differences in total rake between blades at each radius of the port propeller both in millimetres and percent.

For the port propeller, the results show that all mid-chord points are over-raked relative to the design blade with the largest over-rake occurring in the outer 20 percent of blades. The absolute increases in total rake range from 1.7 mm at the root on blade 3 to 36.4 mm at the tip of blade 6. As for the skew angle, the percentage differences increase rapidly as the roots are approached due to the rapid decrease in the rake of the design blade.

From Table 23, the largest inter-blade differences in millimeters at each radius of the port propeller have absolute values that increase from 4.4 mm between blades 2 and 3 at r/R = 0.95 to 26.0 mm between the tips of blades 4 and 6. The much larger tip differences are due to the significant upstream bending of the outer 5% of blades 4 and 5 relative to the significant downstream bending of the outer 5% of blades 2 and 6 (see Figures 8a and 8c).

Radius r/R	Blade 1	Blade 2	Blade 3	Blade 4	Blade 5	Blade 6	Blade 7
1.000	19.91	28.11	19.81	10.36	13.81	36.41	21.18
0.975	21.92	27.14	21.86	20.97	21.21	26.62	21.77
0.950	23.81	26.04	21.67	23.55	22.42	23.86	24.51
0.900	22.86	17.33	21.11	20.27	22.55	25.16	23.58
0.850	22.21	13.81	17.76	20.30	21.52	23.71	20.39
0.800	19.22	12.78	15.17	18.31	19.51	18.80	16.57
0.750	18.44	11.92	14.22	16.02	17.08	16.33	14.24
0.700	15.16	7.91	11.95	13.01	12.90	13.74	10.83
0.650	14.14	6.37	7.65	10.80	10.06	13.51	10.01
0.600	14.99	8.31	6.68	9.82	10.81	13.24	11.19
0.500	14.68	11.69	7.59	9.96	14.22	15.40	13.15
0.400	16.27	14.74	7.14	11.62	10.73	14.58	14.11
0.300	12.43	11.27	7.43	10.79	11.02	13.54	12.07
0.250	4.01	2.83	1.74	5.69	6.81	9.67	4.24

Table 21. *Total Rake Differences (in Millimetres) Relative to Design for the Port Propeller.*

Radius r/R	Blade 1	Blade 2	Blade 3	Blade 4	Blade 5	Blade 6	Blade 7
1.000	13.28	18.76	13.22	6.91	9.21	24.29	14.13
0.975	15.10	18.69	15.05	14.44	14.61	18.33	14.99
0.950	16.90	18.49	15.38	16.72	15.92	16.94	17.40
0.900	17.39	13.18	16.06	15.42	17.15	19.14	17.94
0.850	18.20	11.32	14.55	16.63	17.63	19.42	16.71
0.800	17.06	11.34	13.46	16.25	17.31	16.68	14.71
0.750	17.86	11.54	13.77	15.51	16.54	15.81	13.79
0.700	16.15	8.42	12.72	13.85	13.74	14.63	11.54
0.650	16.73	7.53	9.05	12.78	11.91	15.98	11.84
0.600	19.87	11.01	8.85	13.02	14.32	17.54	14.83
0.500	25.90	20.63	13.39	17.58	25.09	27.18	23.20
0.400	42.95	38.91	18.83	30.66	28.31	38.47	37.24
0.300	65.03	58.93	38.90	56.45	57.62	70.83	63.14
0.250	39.91	28.08	17.30	56.51	67.69	96.17	42.20

Table 22. *Total Rake Differences (in Percent) Relative to Design for the Port Propeller.*

Radius r/R	Millimetres	Percent	Blades
1.000	26.05	17.38	4 & 6
0.975	6.17	4.25	2 & 4
0.950	4.37	3.10	2 & 3
0.900	7.83	5.96	2 & 6
0.850	9.90	8.11	2 & 6
0.800	6.73	5.97	2 & 5
0.750	6.52	6.31	1 & 2
0.700	7.25	7.72	1 & 2
0.650	7.77	9.20	1 & 2
0.600	8.31	11.01	1 & 3
0.500	7.81	13.78	3 & 6
0.400	9.13	24.10	1 & 3
0.300	6.11	31.96	3 & 6
0.250	7.93	78.83	3 & 6

Table 23. *Maximum Inter-Blade Differences in Total Rake for the Port Propeller.*

Tables 24 through 26 provide the corresponding rake differences for the starboard propeller. The results show that all mid-chord points are over-raked relative to the design blade except for the two root-most sections. As for the port propeller, the largest values of over-rake occur in the outer 20 percent of blades. Unlike the port propeller which has all sections over-raked, the two root-most sections on the starboard propeller have decreases in rake relative to design ranging from -1.0 mm at the 30% radius on blades 3 and 4 to -19.6 mm at the 25% radius on blade 2. The absolute increases in total rake range from 0.2 mm at the r/R = 0.3 on blade 1 to 20.5 mm at r/R = 0.975 on blade 3. As for the port propeller, the percentage differences increase rapidly as the roots are approached due to the rapid decrease in the rake of the design blade.

Unlike the port propeller, Table 26 shows the largest inter-blade differences in millimetres for the starboard propeller occurring at the root instead of the tip. Blade-to-blade differences have absolute values increasing from 2.9 mm between blades 2 and 4 at r/R = 0.5 to 13.8 mm between blades 2 and 7 at r/R = 0.25. For outer radii, the largest inter-blade rake differences for the starboard propeller are 8.4 mm between the tips of blades 1 and 6.

Radius r/R	Blade 1	Blade 2	Blade 3	Blade 4	Blade 5	Blade 6	Blade 7
1.000	11.21	19.18	17.61	15.71	15.92	19.57	18.05
0.975	15.66	15.91	20.52	17.15	12.53	14.65	16.79
0.950	12.80	16.75	18.12	15.97	12.80	16.62	18.10
0.900	12.85	14.78	13.51	17.26	15.35	12.36	20.20
0.850	12.40	12.88	13.81	19.68	14.64	11.86	18.14
0.800	8.76	10.99	10.28	12.90	12.29	9.73	12.46
0.750	8.76	9.38	8.63	7.54	12.05	7.90	10.14
0.700	7.30	4.23	6.47	3.30	9.19	4.29	5.39
0.650	5.97	1.33	4.38	1.97	7.18	1.60	2.92
0.600	6.65	2.49	4.17	4.02	7.26	1.49	4.18
0.500	7.65	5.63	7.89	8.54	7.85	6.91	7.06
0.400	6.66	2.33	7.27	7.79	8.44	8.07	8.68
0.300	0.24	-6.31	-1.03	-0.99	2.41	0.72	5.41
0.250	-11.52	-19.62	-14.19	-13.26	-10.44	-9.58	-5.79

Table 24. *Total Rake Differences (in Millimetres) Relative to Design for the Starboard Propeller.*

Radius r/R	Blade 1	Blade 2	Blade 3	Blade 4	Blade 5	Blade 6	Blade 7
1.000	7.48	12.80	11.75	10.48	10.62	13.06	12.04
0.975	10.78	10.96	14.13	11.81	8.63	10.09	11.56
0.950	9.09	11.89	12.87	11.34	9.09	11.80	12.85
0.900	9.77	11.24	10.27	13.13	11.68	9.40	15.37
0.850	10.16	10.55	11.32	16.12	11.99	9.71	14.86
0.800	7.78	9.75	9.12	11.45	10.91	8.64	11.06
0.750	8.49	9.08	8.35	7.31	11.66	7.65	9.81
0.700	7.77	4.51	6.89	3.52	9.79	4.57	5.74
0.650	7.07	1.57	5.18	2.33	8.49	1.89	3.46
0.600	8.81	3.30	5.53	5.34	9.62	1.98	5.55
0.500	13.50	9.94	13.92	15.07	13.85	12.19	12.46
0.400	17.58	6.14	19.19	20.56	22.28	21.30	22.90
0.300	1.26	-32.98	-5.39	-5.15	12.63	3.79	28.30
0.250	-114.46	-194.98	-141.00	-131.81	-103.78	-95.23	-57.50

Table 25. *Total Rake Differences (in Percent) Relative to Design for the Starboard Propeller.*

Radius r/R	Millimetres	Percent	Blades
1.000	8.36	5.58	1 & 6
0.975	7.99	5.50	3 & 5
0.950	5.32	3.78	1,5 & 3
0.900	7.84	5.96	6 & 7
0.850	7.82	6.41	4 & 6
0.800	4.14	3.67	1 & 4
0.750	4.51	4.37	4 & 5
0.700	5.89	6.27	4 & 5
0.650	5.85	6.92	2 & 5
0.600	5.77	7.65	5 & 6
0.500	2.91	5.14	2 & 4
0.400	6.35	16.76	2 & 7
0.300	11.72	61.31	2 & 7
0.250	13.83	137.48	2 & 7

Table 26. *Maximum Inter-Blade Differences in Total Rake for the Starboard Propeller.*

Figures 8a and 8b are plots of the total rake versus radius fraction for all measured sections on the port and starboard propellers, respectively. The radial distribution of total rake for the design blade is also plotted using a dashed line. Figures 8c and 8d provide a closer look at these results over the outer 30% of blades. A comparison of Figures 8c and 8d shows the much larger inter-blade variation in rake approaching the tips of port propeller blades relative to starboard blades. It is particularly noteworthy that these larger differences are due to the tips of blades 4 and 5 of the port propeller bending sharply upstream between 97.5% of the tip radius and the tip.

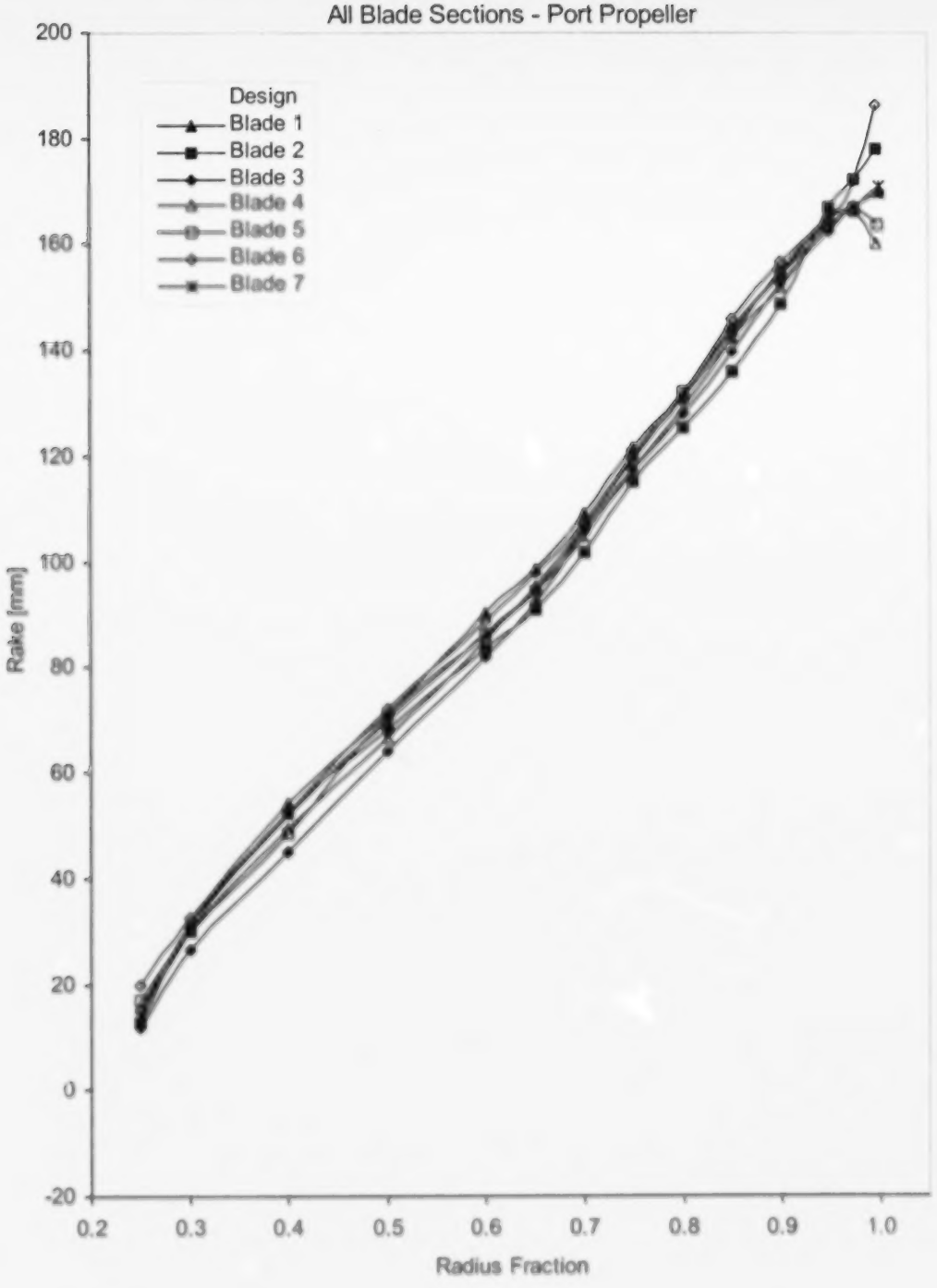


Figure 8a. *Radial Rake Distribution for All Blade Sections of the Port Propeller.*

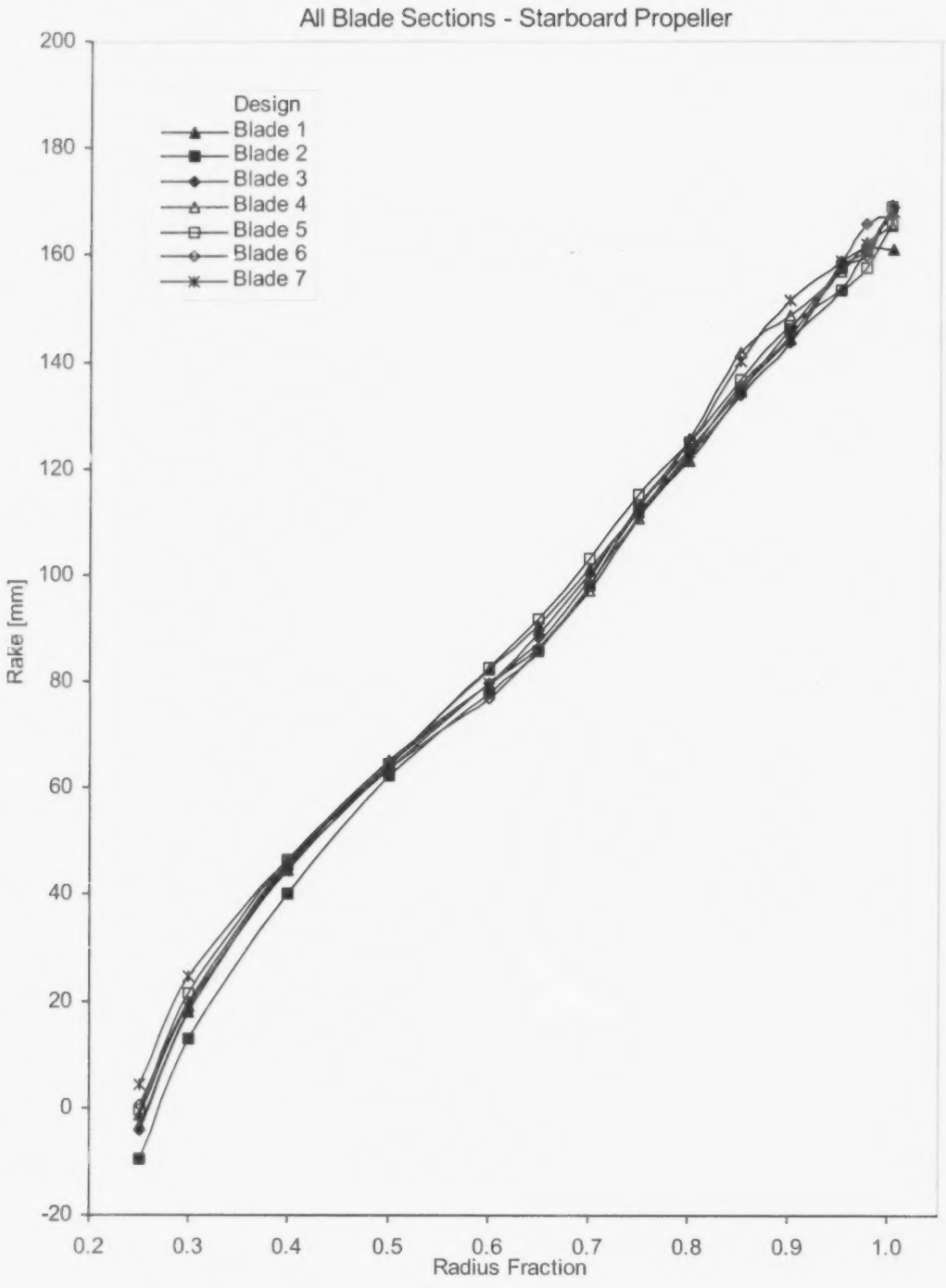


Figure 8b. *Radial Rake Distribution for All Blade Sections of the Starboard Propeller.*

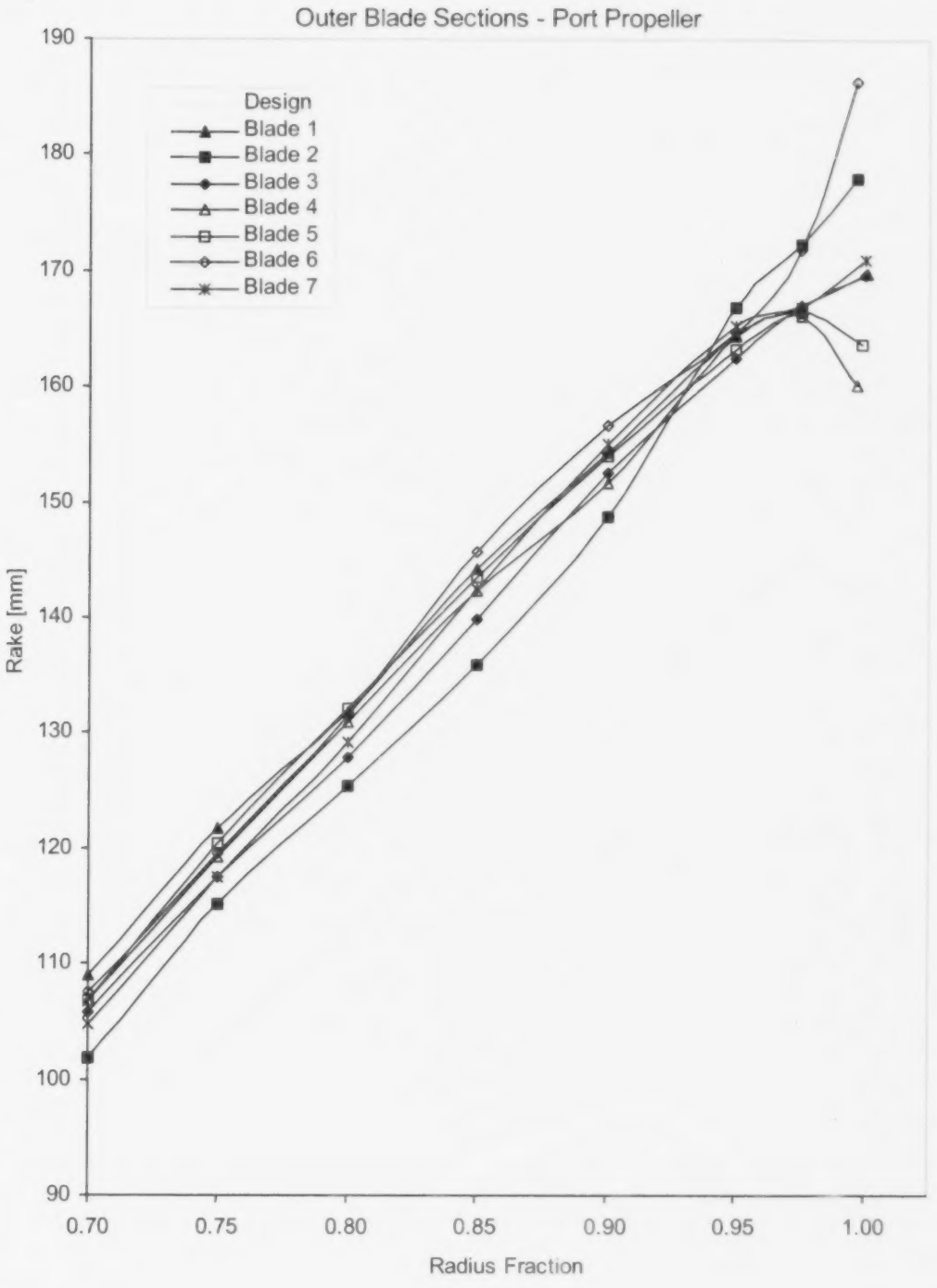


Figure 8c. *Radial Rake Distribution for Outer Blade Sections of the Port Propeller.*

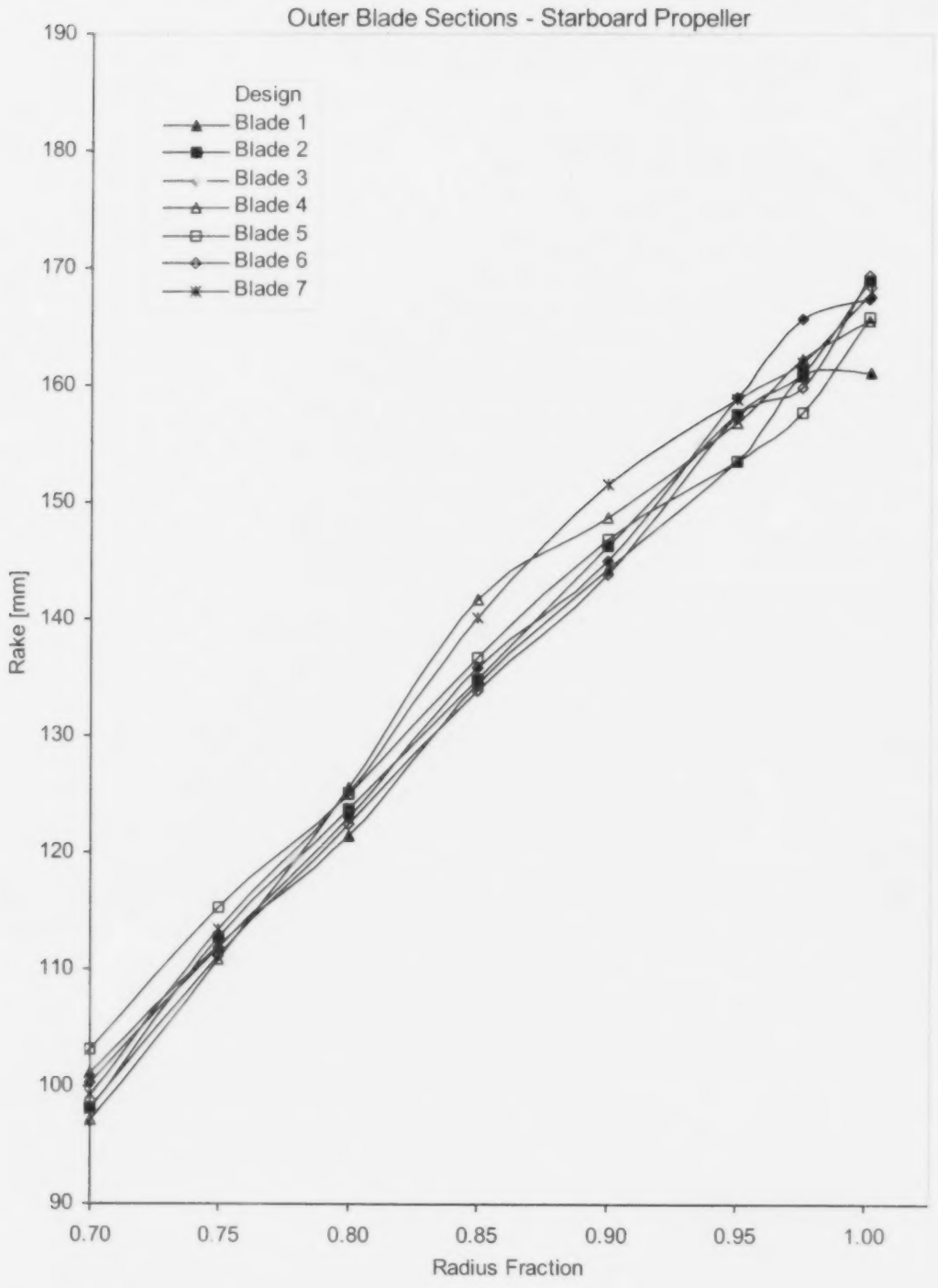


Figure 8d. *Radial Rake Distribution for Outer Blade Sections of the Starboard Propeller*

3.2 Blade Edge Outlines

This section compares the projected outlines of the measured edges of propeller blades to the corresponding edge outlines for the design blade. Three-dimensional outlines of blade edges are viewed from two perpendicular directions with each blade located at its top vertical reference position. Figures 9 through 22 give the projected views of the edge outlines for each of the 7 measured blades of the port and starboard propellers. The odd-numbered figures gives views for blades 1 through 7 of the port propeller, while the even-numbered figures give the corresponding views for the starboard propeller. The bottom outline in each figure is a view from downstream looking perpendicular to the propeller rotation plane, and the top outline is a view looking down on the blade from above. In each figure, the edge outlines for the design blade are shown using a dashed line.

As for the mid-chord skew comparisons in Section 3.1.3, comparisons of these outlines are performed by rotating the angular coordinates of the edges of each blade until the root-most leading edge angle is matched to that of the design blade in its upward vertical reference position. Overall these figures show the combined effect of the geometric differences described in the previous section on the shape of the blade edge outlines in three dimensions.

The effect of the significant increases in pitch and rake relative to design is particularly evident for the outer parts of the port propeller blades. In the previous section, the total rake is defined and compared at only the mid-chord locations of each section. The edge outline views for port propeller blades show the combined effect of the larger pitch and rake differences with the trailing edges further downstream relative to design than the leading edges. The largest decreases in chord length are particularly evident over the outer 20% of most port propeller blades. The largest decrease in skew angle is evident at the tip of blade 4 of the port propeller.

The edge outlines for the starboard propeller blades are generally much closer to design than those of the port propeller, with larger upstream-directed rake differences evident near the roots in the overhead views of most blades. Although not quite as much as for the port propeller, the trailing edges of outer radius sections of some starboard blades are also seen to be further downstream relative to design than the leading edges. The larger increases in chord length are evident on the outermost measured sections of starboard propeller blades.

The overhead views give an indication of the relative orientation of the edge slopes relative to the mean inflow on outer radius sections. In normal straight-ahead conditions, the component of inflow due to blade rotation dominates for the outer sections, coming in from either the left or right-hand sides in these views for port and starboard blades, respectively. The slope changes relative to the inflow direction are seen to be significant for the over-pitched sections at outer radii for blades of the port propeller. These changes increase the geometric angles of attack of inflows relative to the section chord lines, therefore decreasing the pressures and lowering the inception speeds for cavitation forming near the tips on the back or upstream side of the blades.

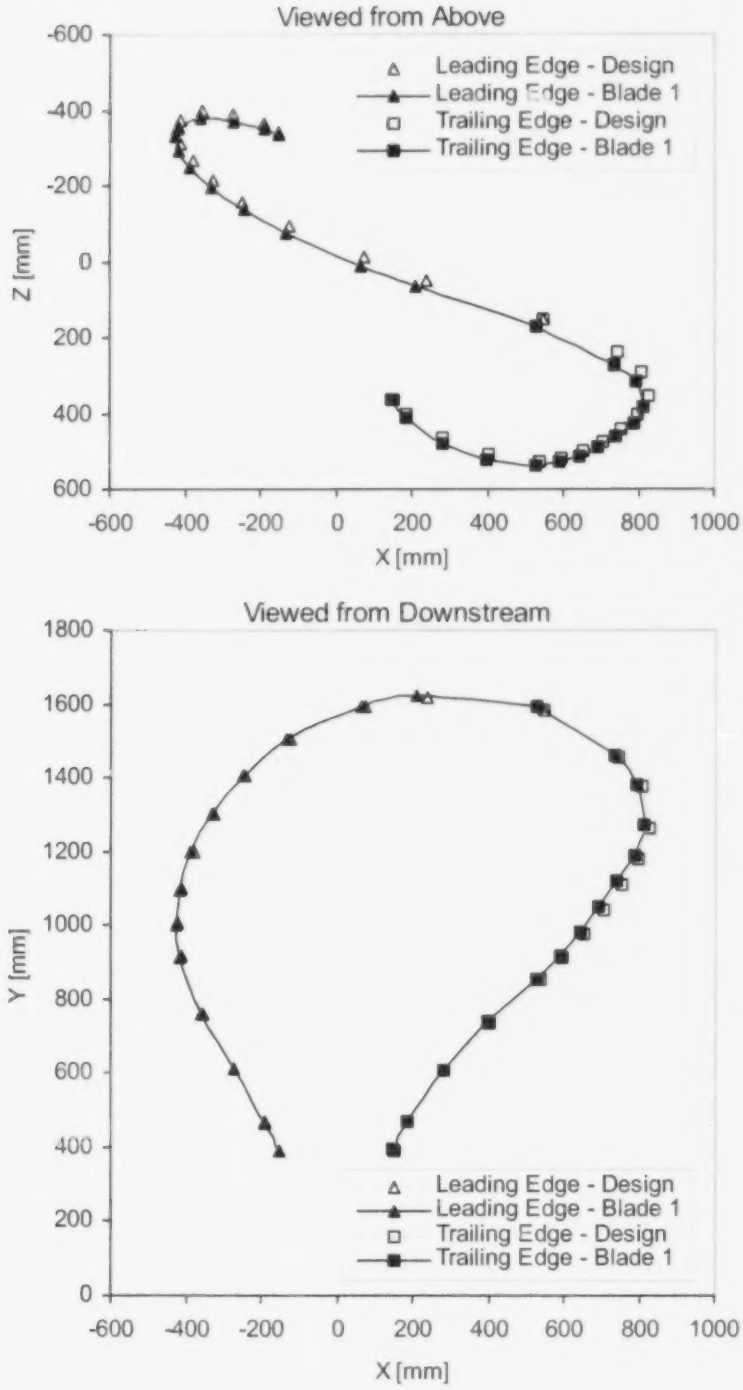


Figure 9. *Projected Views of the Edge Outline for Blade 1 of the Port Propeller.*

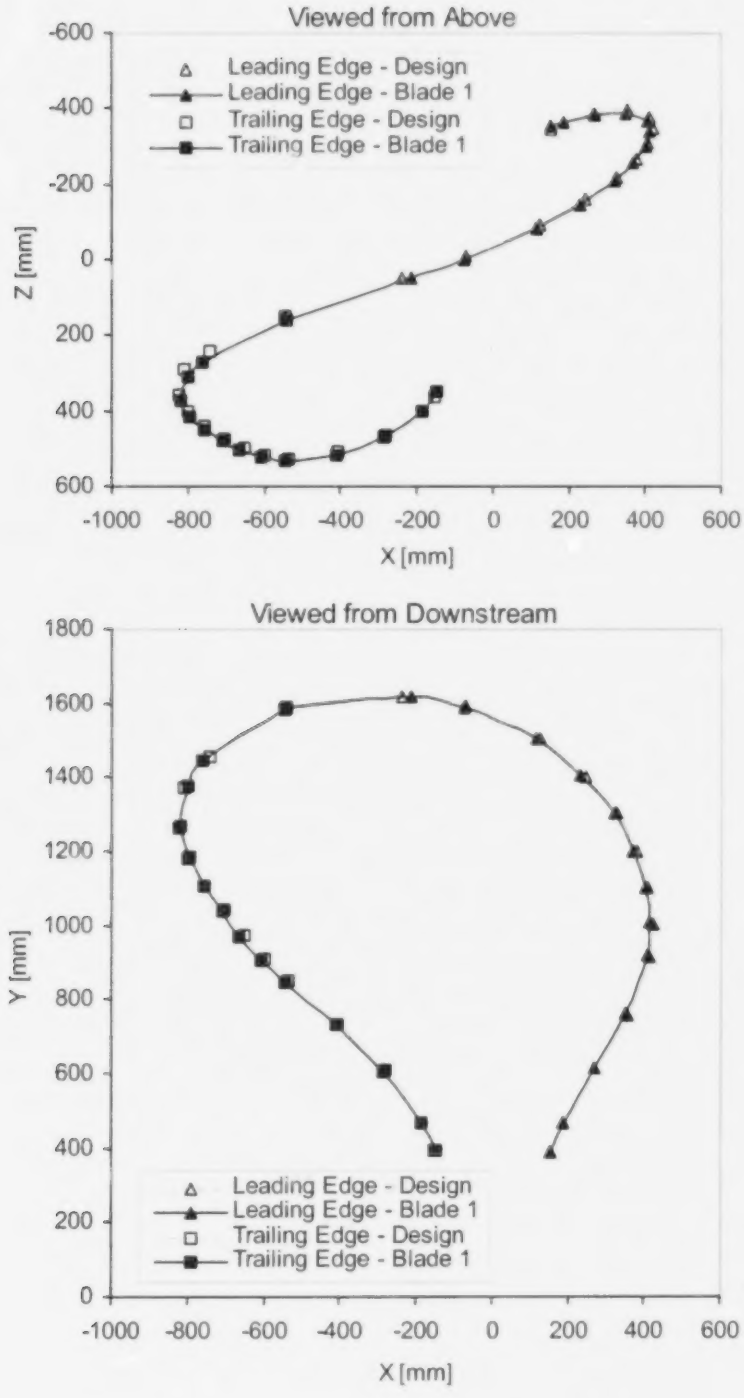


Figure 10. *Projected Views of the Edge Outline for Blade 1 of the Starboard Propeller.*

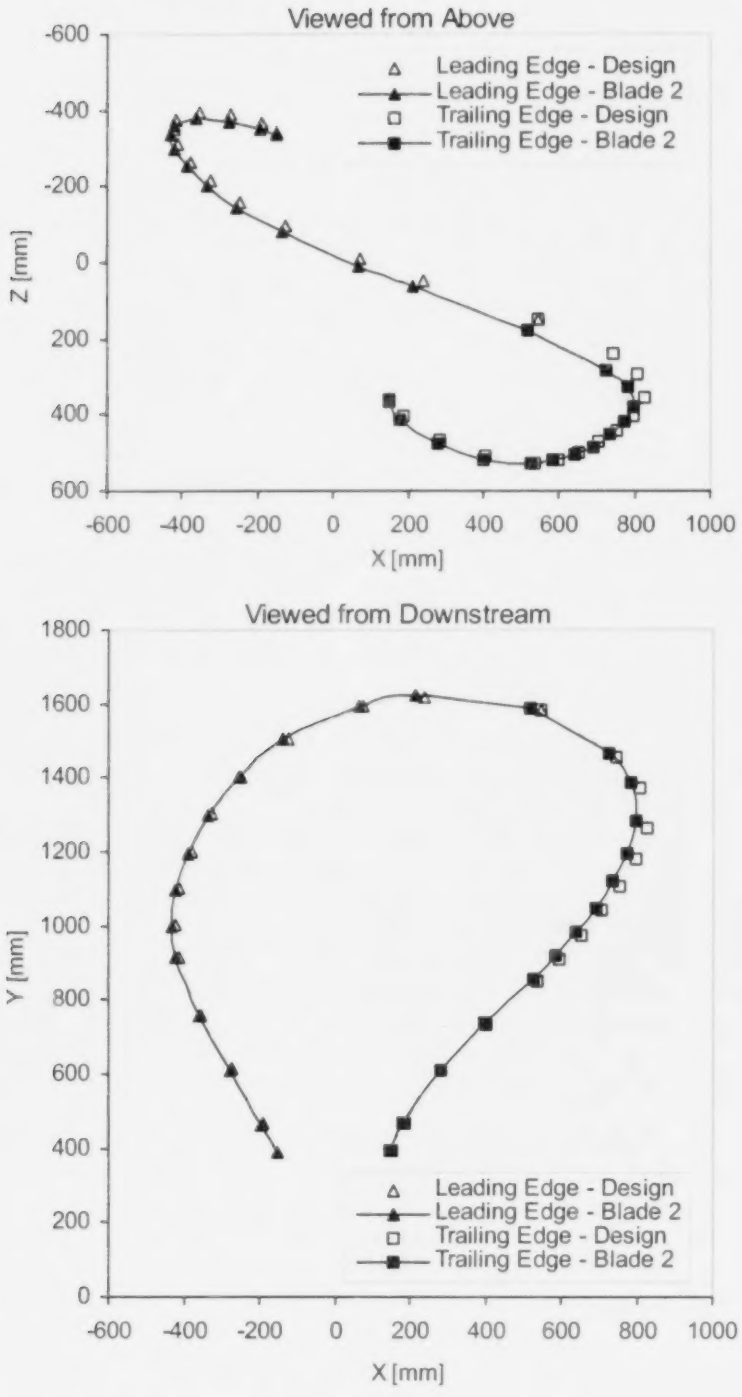


Figure 11. *Projected Views of the Edge Outline for Blade 2 of the Port Propeller.*

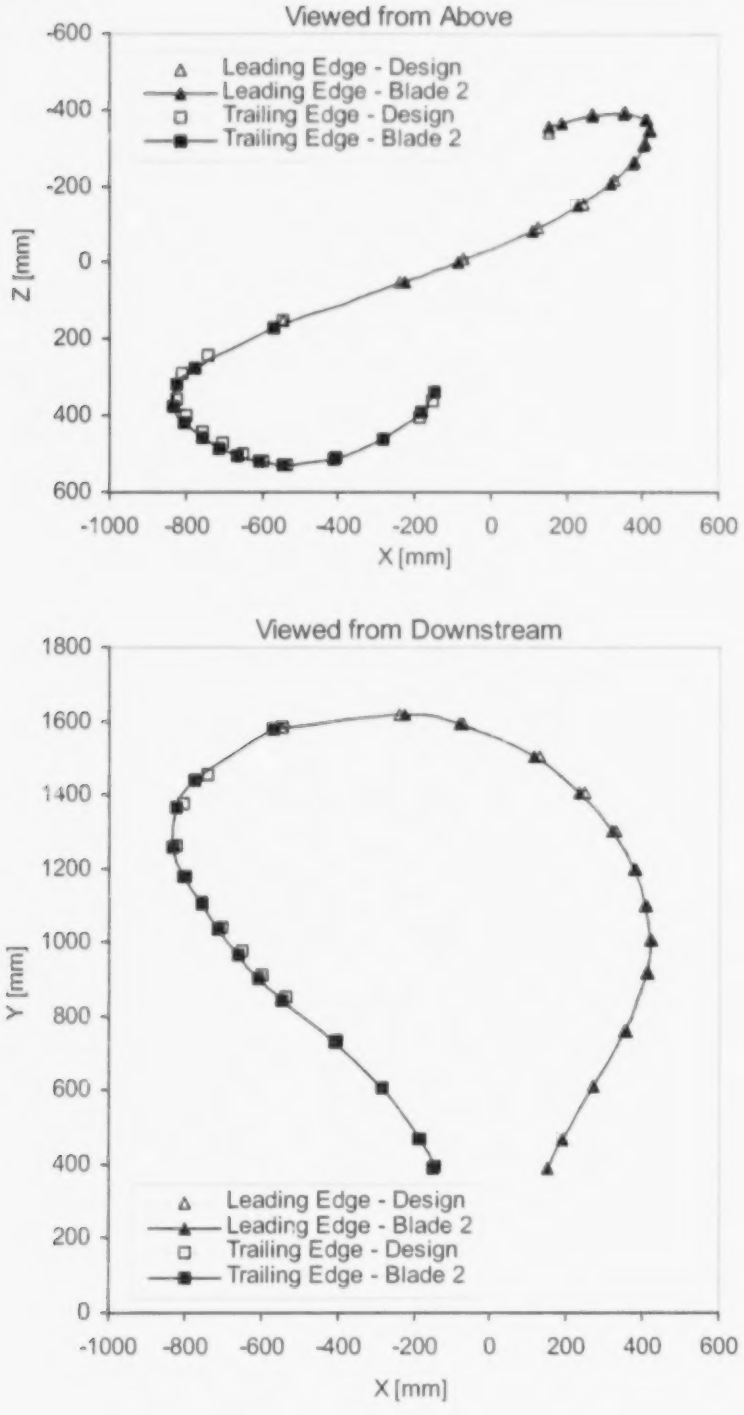


Figure 12. *Projected Views of the Edge Outline for Blade 2 of the Starboard Propeller.*

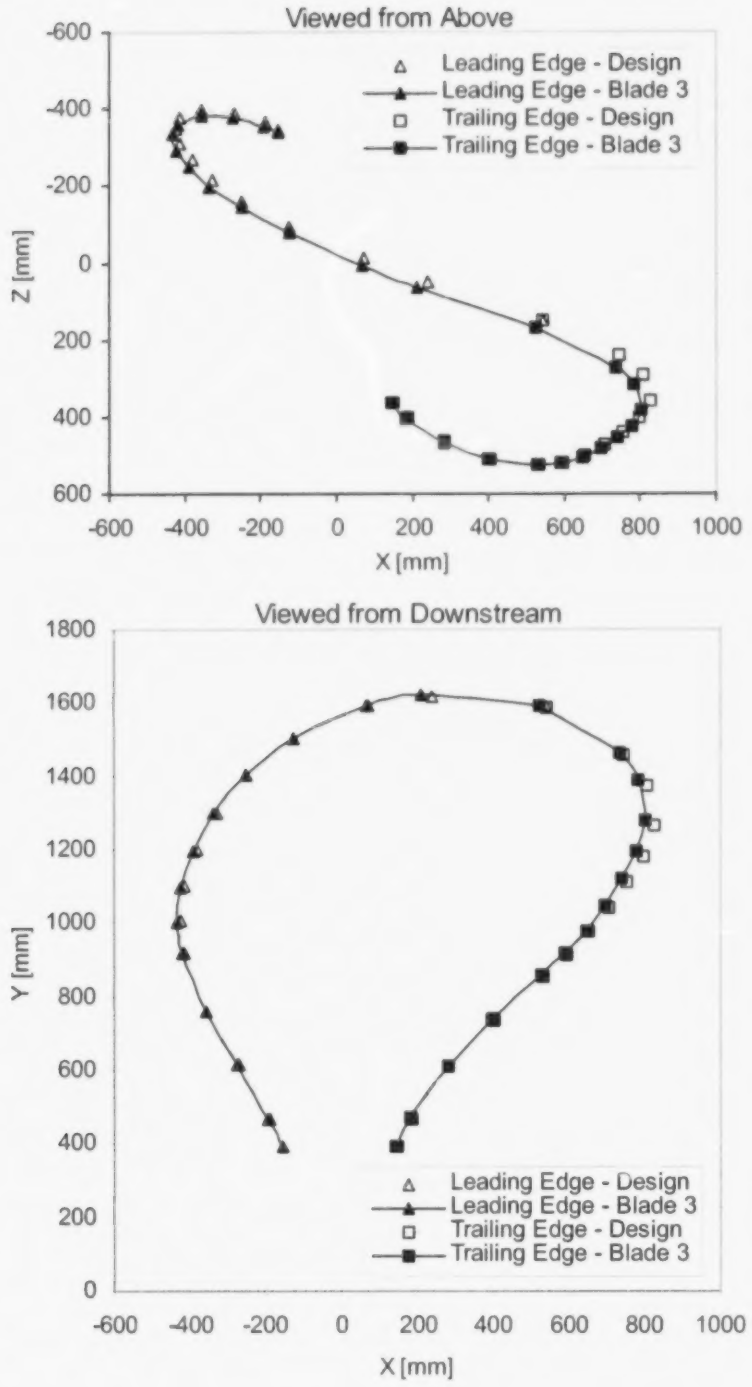


Figure 13. *Projected Views of the Edge Outline for Blade 3 of the Port Propeller.*

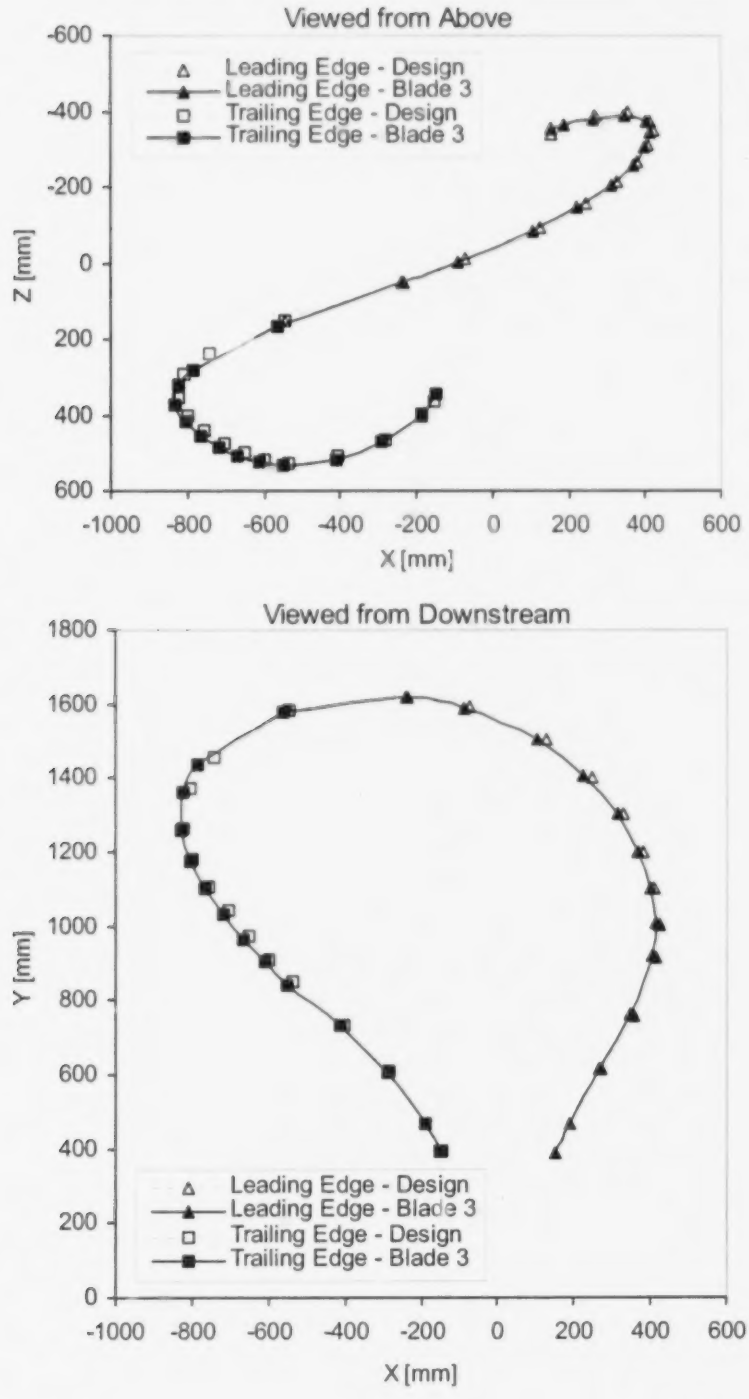


Figure 14. *Projected Views of the Edge Outline for Blade 3 of the Starboard Propeller.*

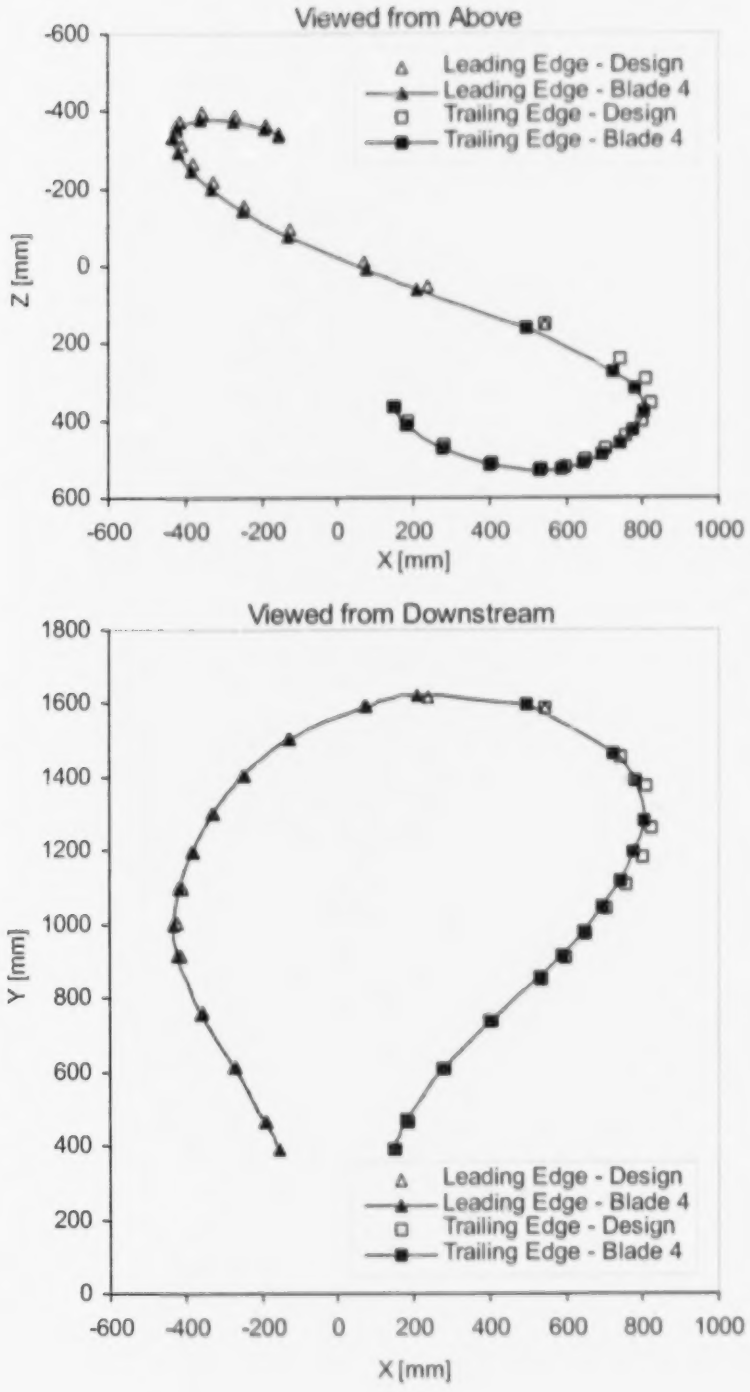


Figure 15. *Projected Views of the Edge Outline for Blade 4 of the Port Propeller.*

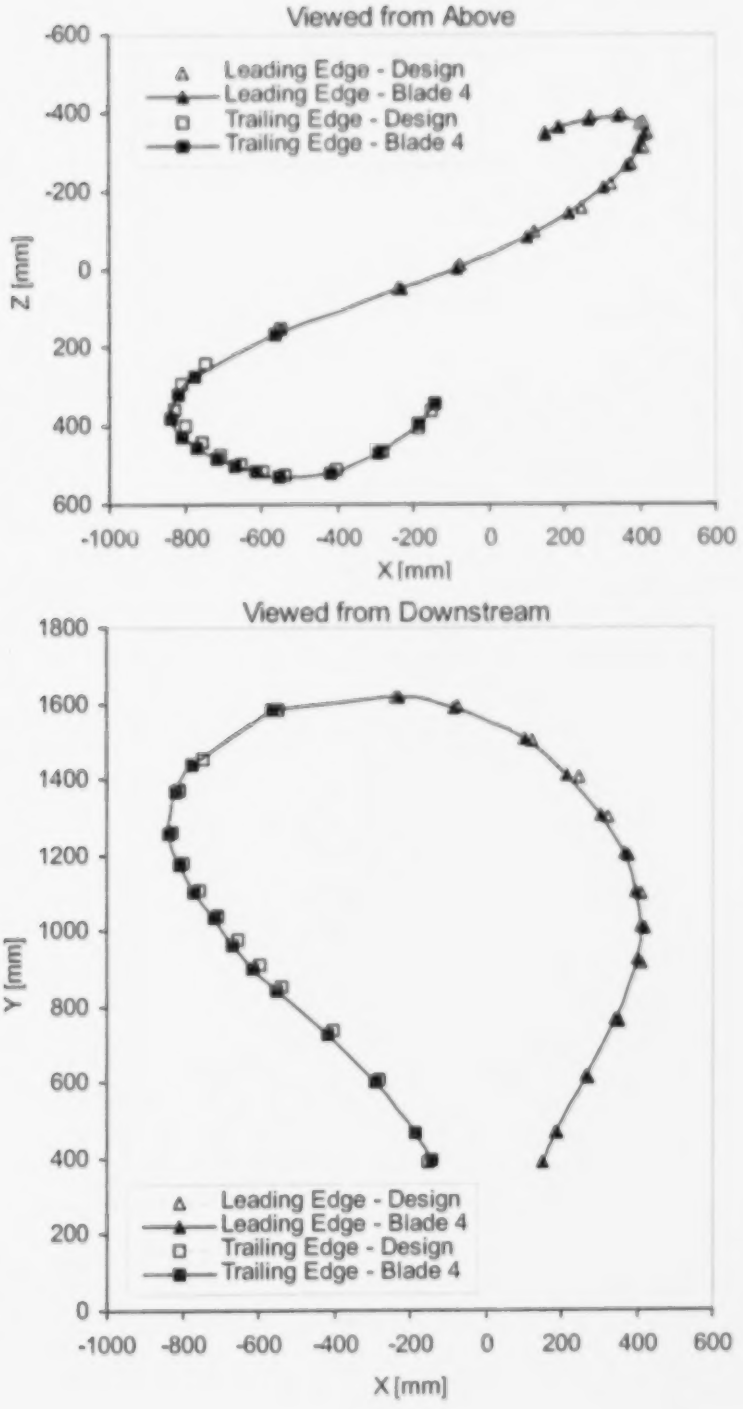


Figure 16. *Projected Views of the Edge Outline for Blade 4 of the Starboard Propeller.*

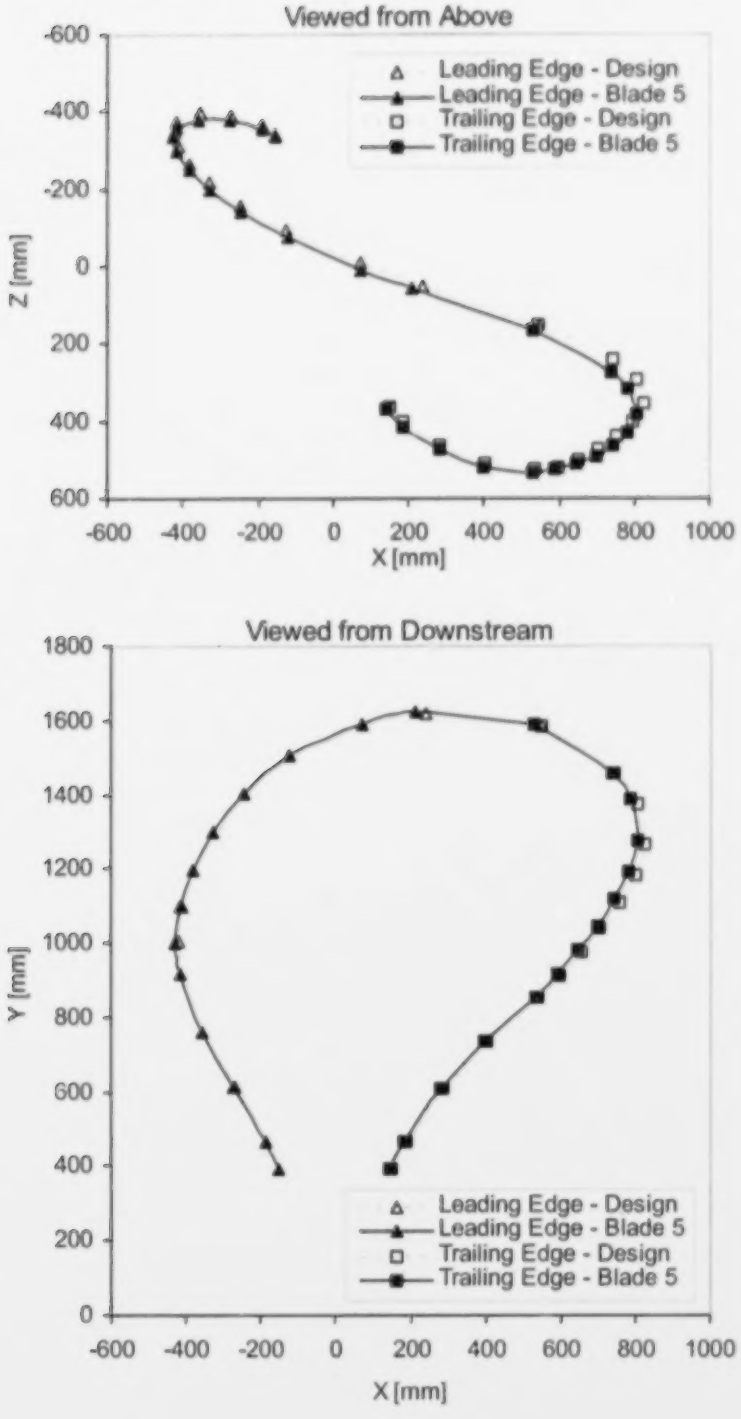


Figure 17. *Projected Views of the Edge Outline for Blade 5 of the Port Propeller.*

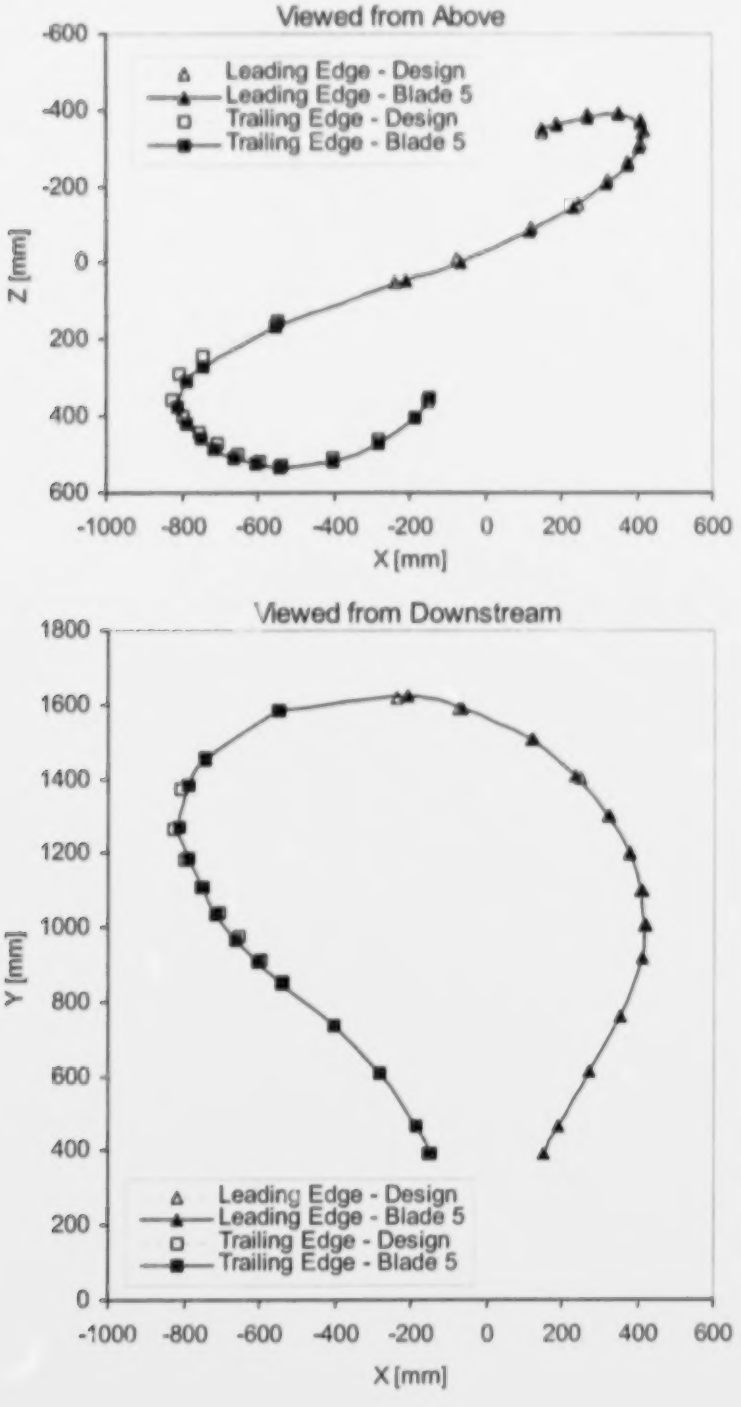


Figure 18. *Projected Views of the Edge Outline for Blade 5 of the Starboard Propeller.*

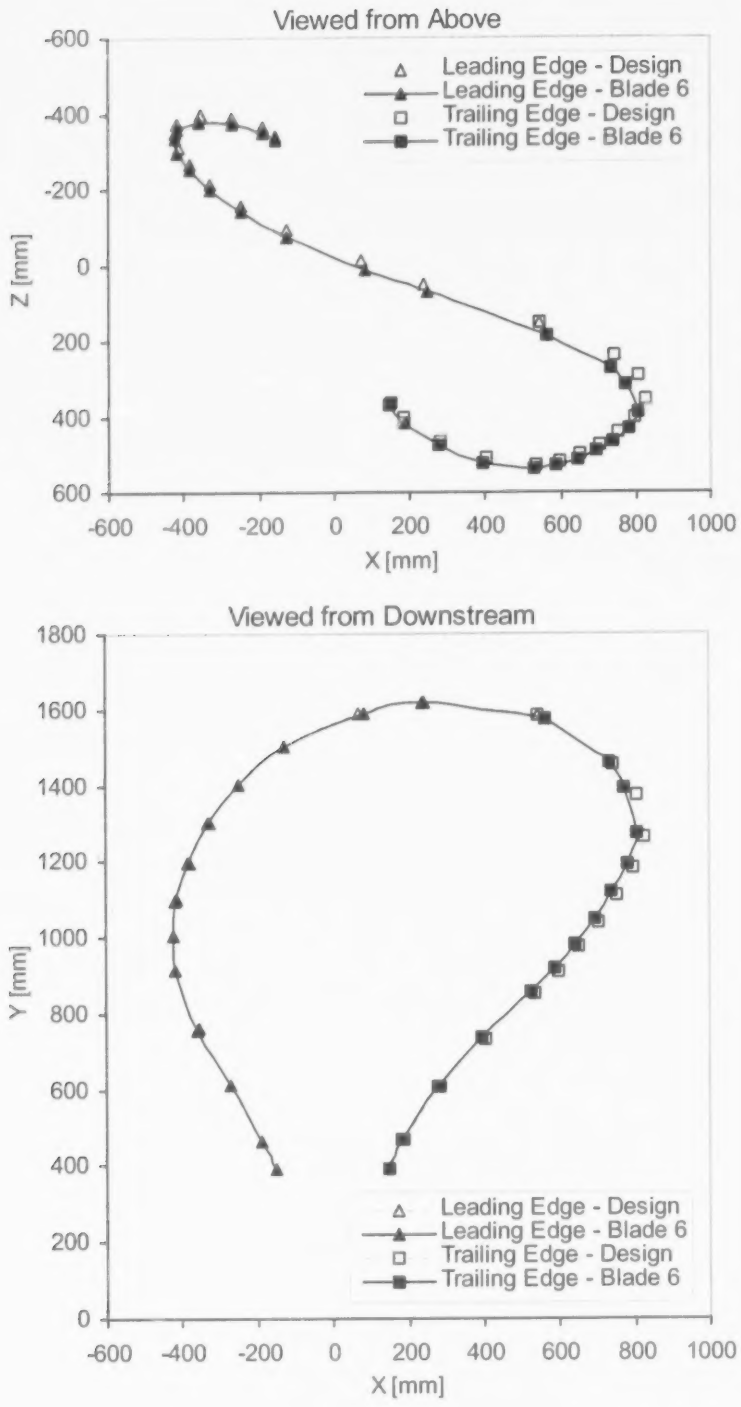


Figure 19. *Projected Views of the Edge Outline for Blade 6 of the Port Propeller.*

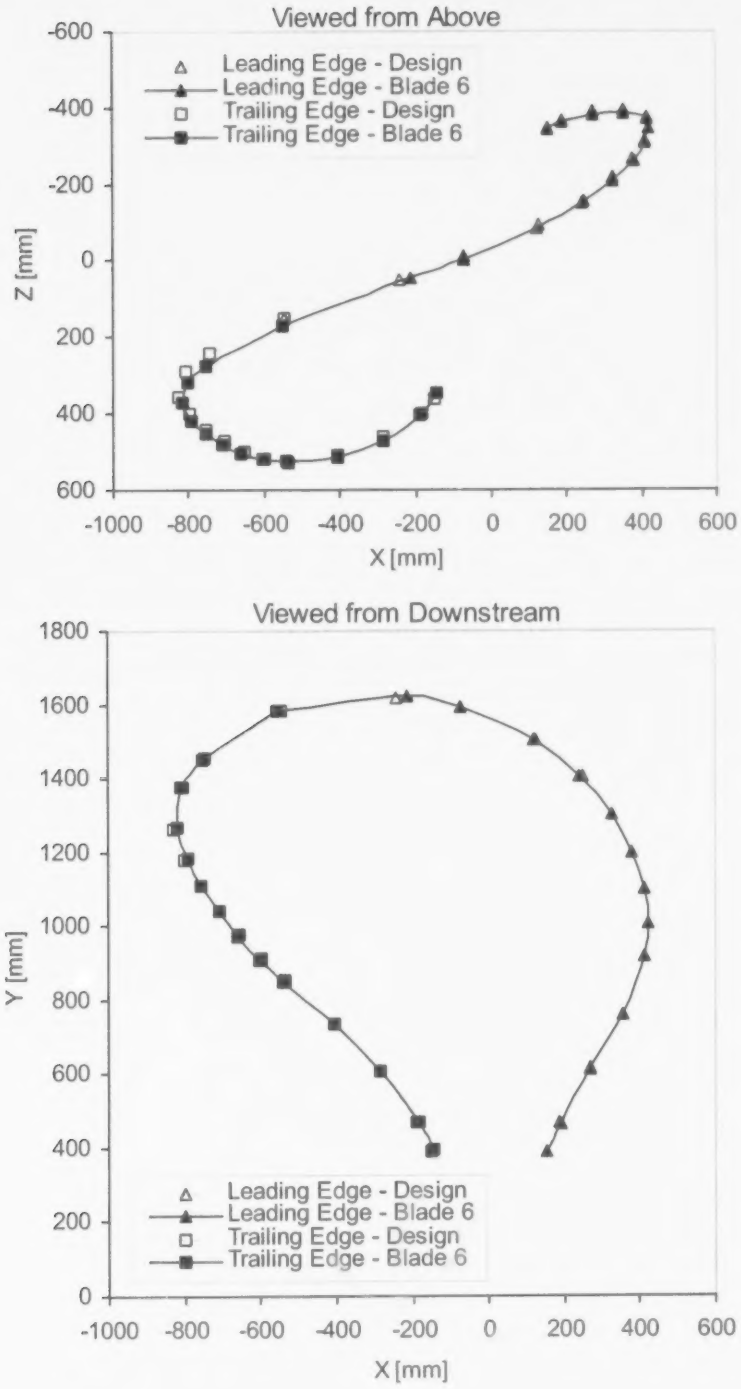


Figure 20. *Projected Views of the Edge Outline for Blade 6 of the Starboard Propeller.*

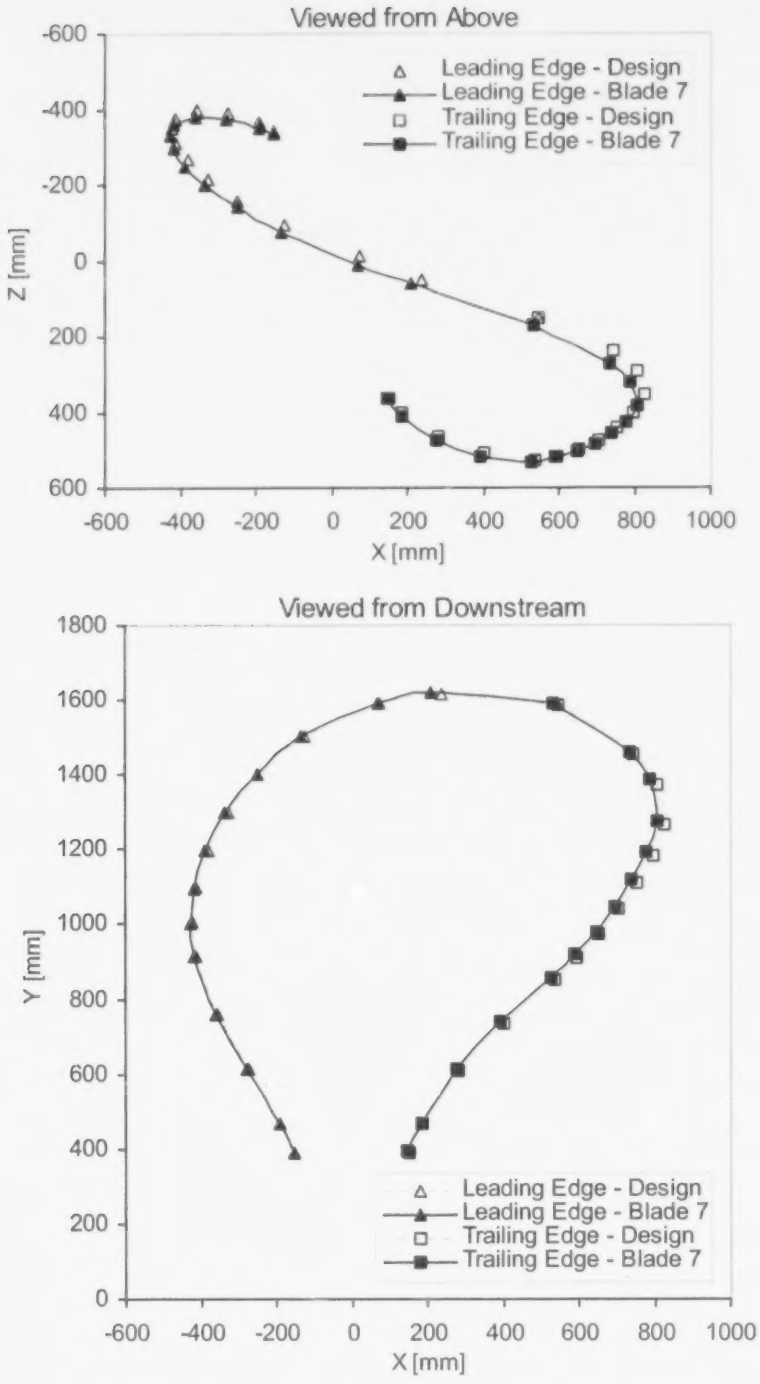


Figure 21. *Projected Views of the Edge Outline for Blade 7 of the Port Propeller.*

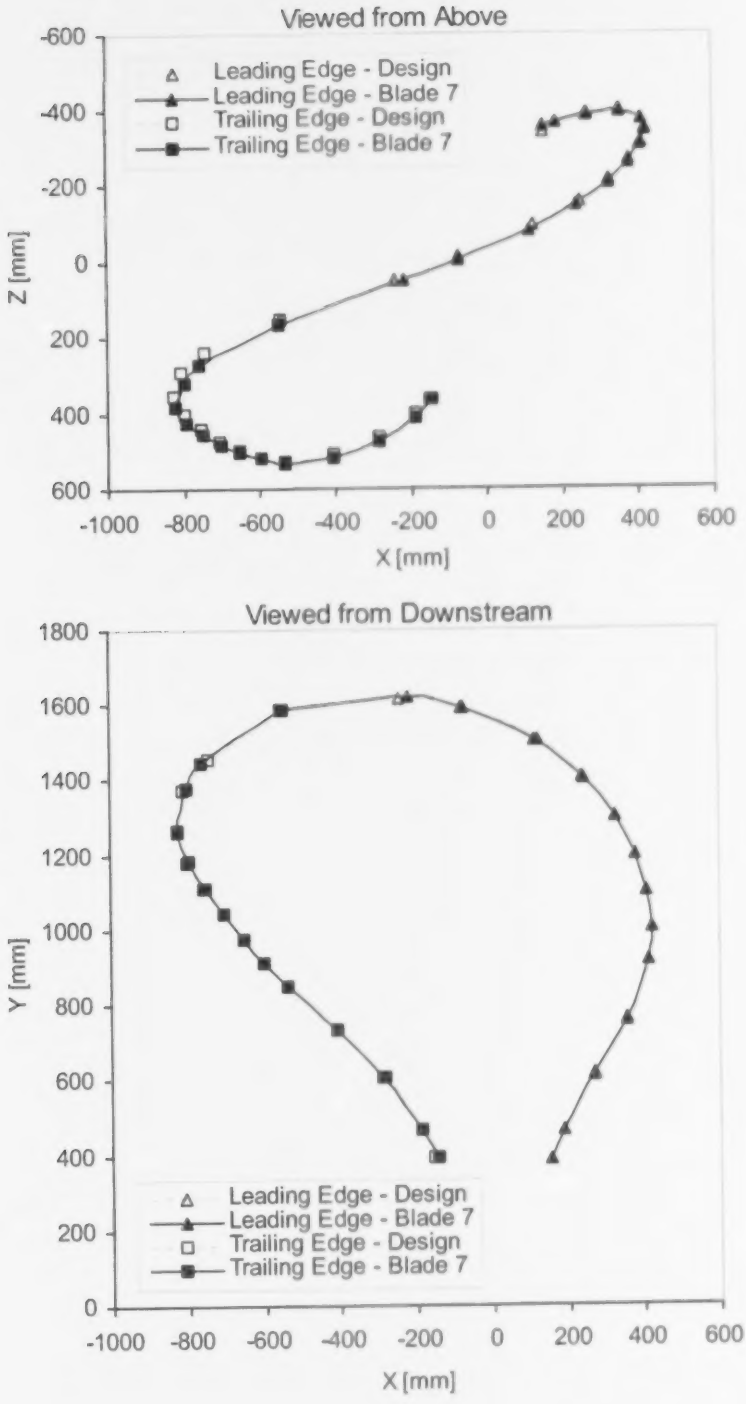


Figure 22. *Projected Views of the Edge Outline for Blade 7 of the Starboard Propeller.*

3.3 Expanded Blade Sections

In this section of the report, the cross-sectional shapes of constant radius sections in the outer 20% of measured blades are compared to each other and to the corresponding design blade sections. The measured sections, actually located on the surfaces of constant radius cylinders with their chord lines lying along helical arcs, are compared in the following figures using expanded or flattened views where the chord lines appear as straight lines on plots of the vertical coordinate Z versus the circular arc length $r\theta$ at radius r and angle θ. In addition to showing the true pitch angle and chord length of section chord lines, these expanded views show the combined effect of differences in local section thickness and camber measured normal to the chord line.

At each radius, the shapes of the measured sections on each blade were compared by rotating the measured angular coordinates of surface points on both sides through a fixed angle required to match their leading edge angles to those of the design section in its upward vertical reference position. The horizontal scale was also adjusted to set $r\theta = 0$ at the leading edge. Although relative skew angle differences of blade sections were not represented in these views, the true relative differences in section rake were maintained. As described in Section 2.2, the ultrasound thickness measurements near the mid-chord were used to adjust the measured Z coordinates of surface points on sections having a small trailing edge mismatch due to vertical measurement errors with the pitchometer device. By applying half of the vertical adjustment equally to all points on each side of a section, the relative changes to locations of the section chord and mean camber lines due to the thickness adjustment were minimized.

Figures 23 through 27 compare the expanded views of measured sections of the port propeller blades to the corresponding design sections starting with the outermost sections on blades 1 through 7 at a radius fraction of 0.975 in Figures 23a through 23d and proceeding inboard in sequence to sections at a radius fraction of 0.80 in Figures 27a through 27d. In these views, the design sections are illustrated using a dashed line. The sections are drawn with leading edges on the left side of the figures to correspond to the orientation of the blades of the left-handed port propeller rotating outward in their top vertical reference position.

Figures 23a through 23d show the significant over-pitch of the outermost measured sections at $r/R = 0.975$ of the port propeller blades with pitch angles increasing to a maximum of more than 2 degrees above design on blades 2 and 6. With the exception of blade 6, these sections have larger chord lengths than design reaching a maximum chord increase of about 32 mm on blade 5. These sections are over-raked by more than 20 mm with all of the section surface points displaced further downstream than the design section. A maximum over-rake of around 27 mm is evident on blades 2 and 6. Also evident from these figures is the significant blade-to-blade variation in local thickness of the outermost sections, particularly approaching the leading and trailing edges.

Even though the measured surface points in these figures were joined using smoothed lines in Excel, small undulations in the surface shapes of most sections are evident that do not appear in the plots of the design surfaces. This is partly due to the limited accuracy of the vertical surface measurements, although there were some areas on the surfaces that had small bumps and indentations, and some of the leading edges at outer radii had visible surface flats. The surface undulations appear to lessen with decreasing radius and are not evident in the surface plots of the much thicker lower radius sections.

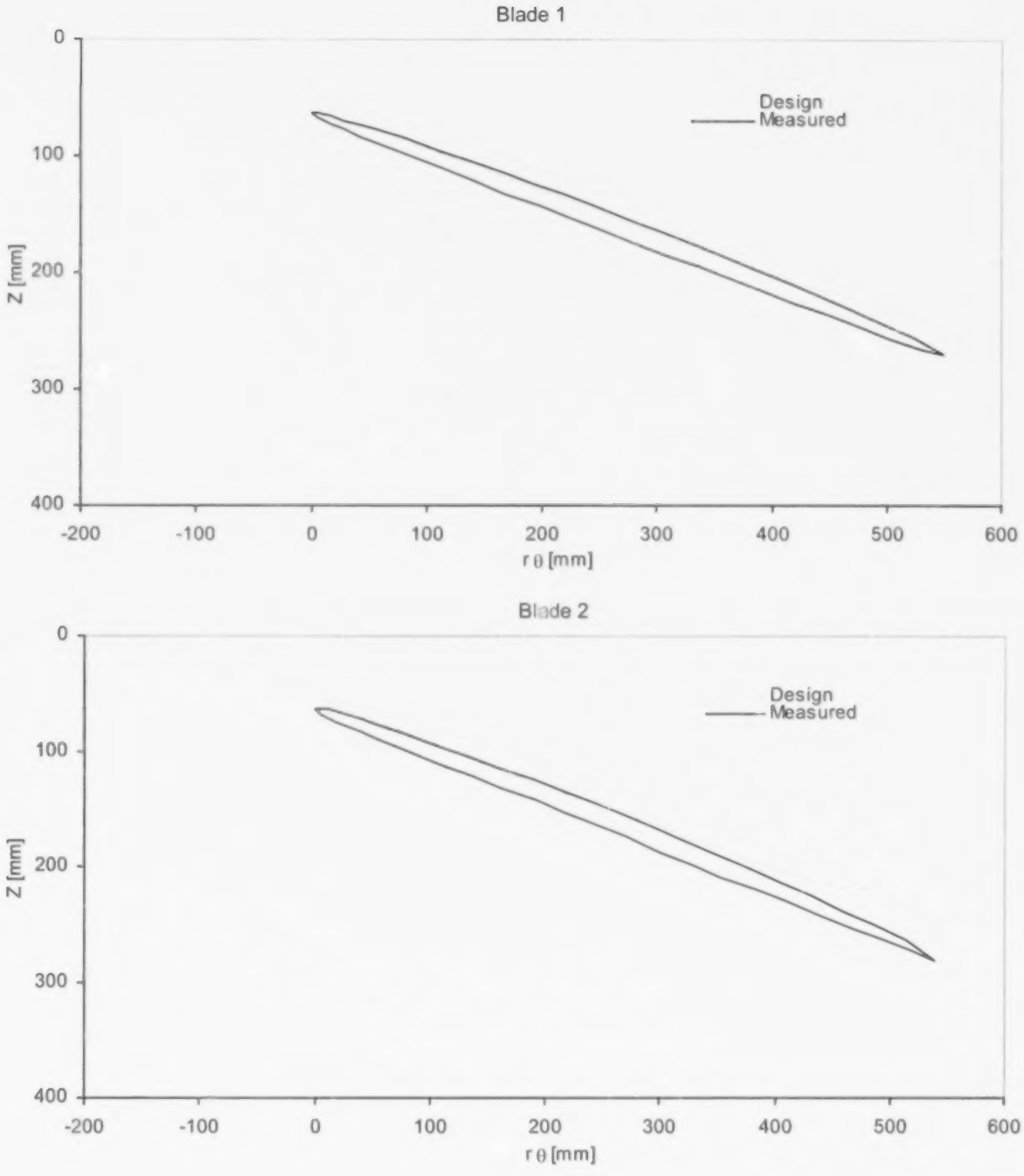


***Figure 23a**. Expanded Sections at a Radius Fraction of 0.975 for Blades 1 and 2 of the Port Propeller.*

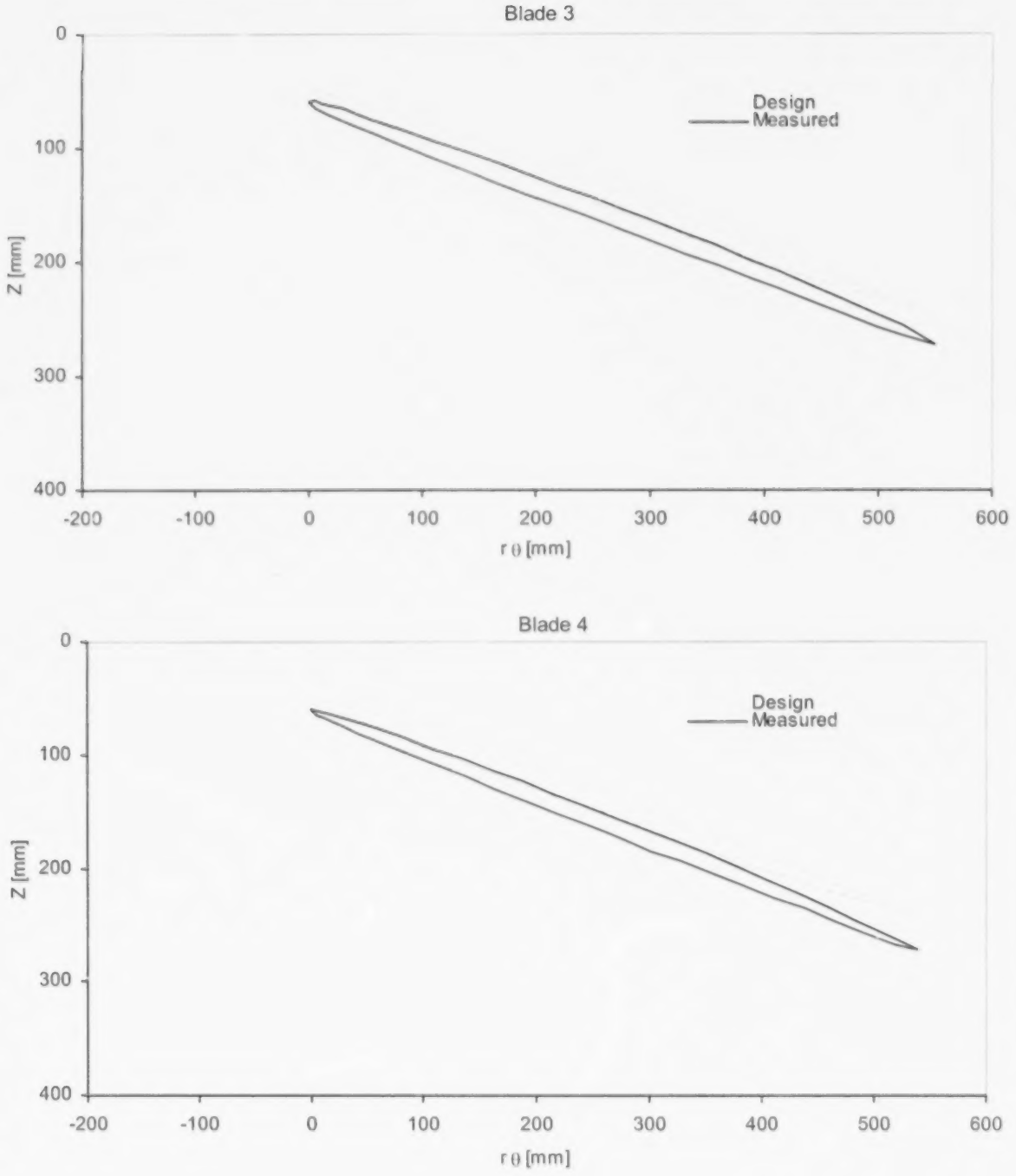


***Figure 23b**. Expanded Sections at a Radius Fraction of 0.975 for Blades 3 and 4 of the Port Propeller.*

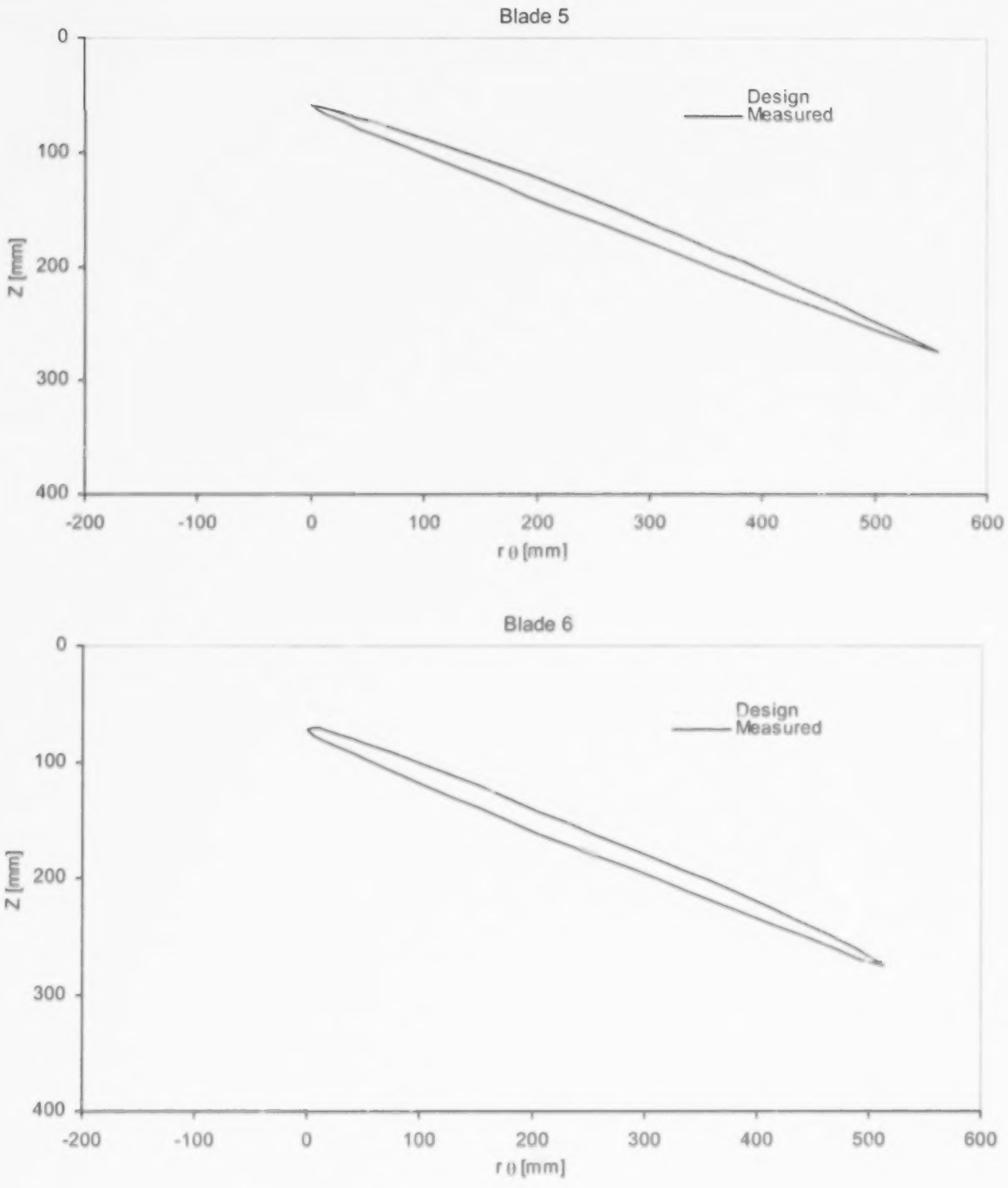


***Figure 23c**. Expanded Sections at a Radius Fraction of 0.975 for Blades 5 and 6 of the Port Propeller.*

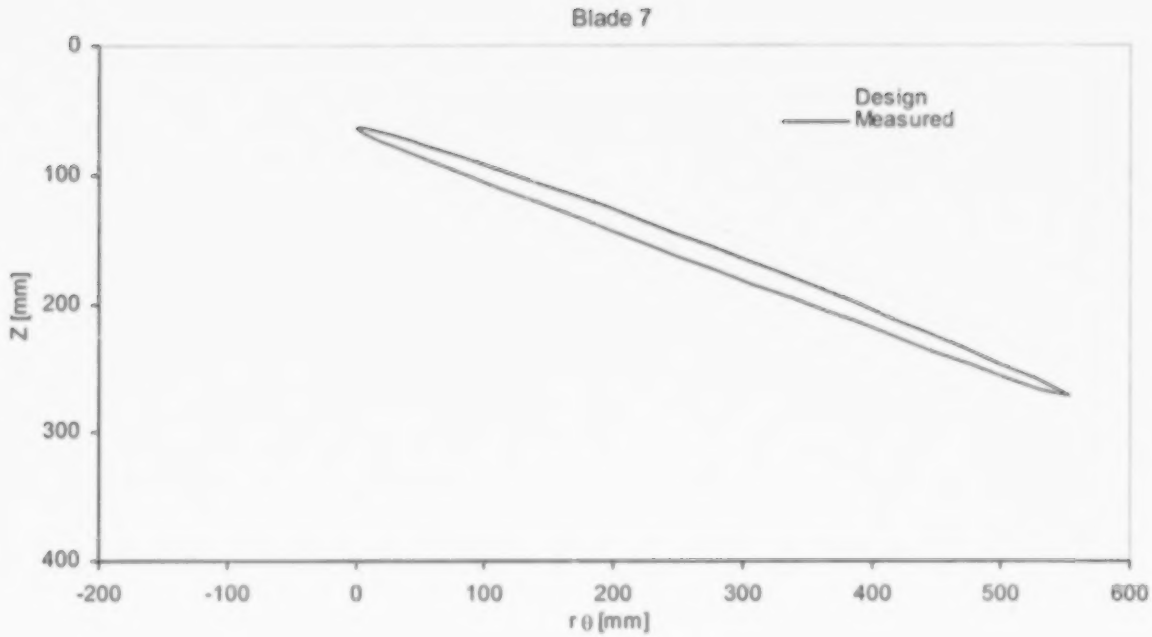


***Figure 23d**. Expanded Section at a Radius Fraction of 0.975 for Blade 7 of the Port Propeller.*

Figures 24a through 24d for outer blade sections at r/R = 0.95 of the port propeller show slightly less over-pitch than the sections at r/R = 0.975 with pitch angles increasing to a maximum of about 1.5 degrees above design on blades 2 and 6. All of these sections have smaller chord lengths than design with chords decreasing by a maximum of about 45 mm on blade 6. As for sections at the outermost radius, these sections are all over-raked by more than 20 mm reaching a maximum over-rake of about 26 mm on blade 2. The sections do not show as much blade-to-blade variation in local thickness as the sections at r/R = 0.975.

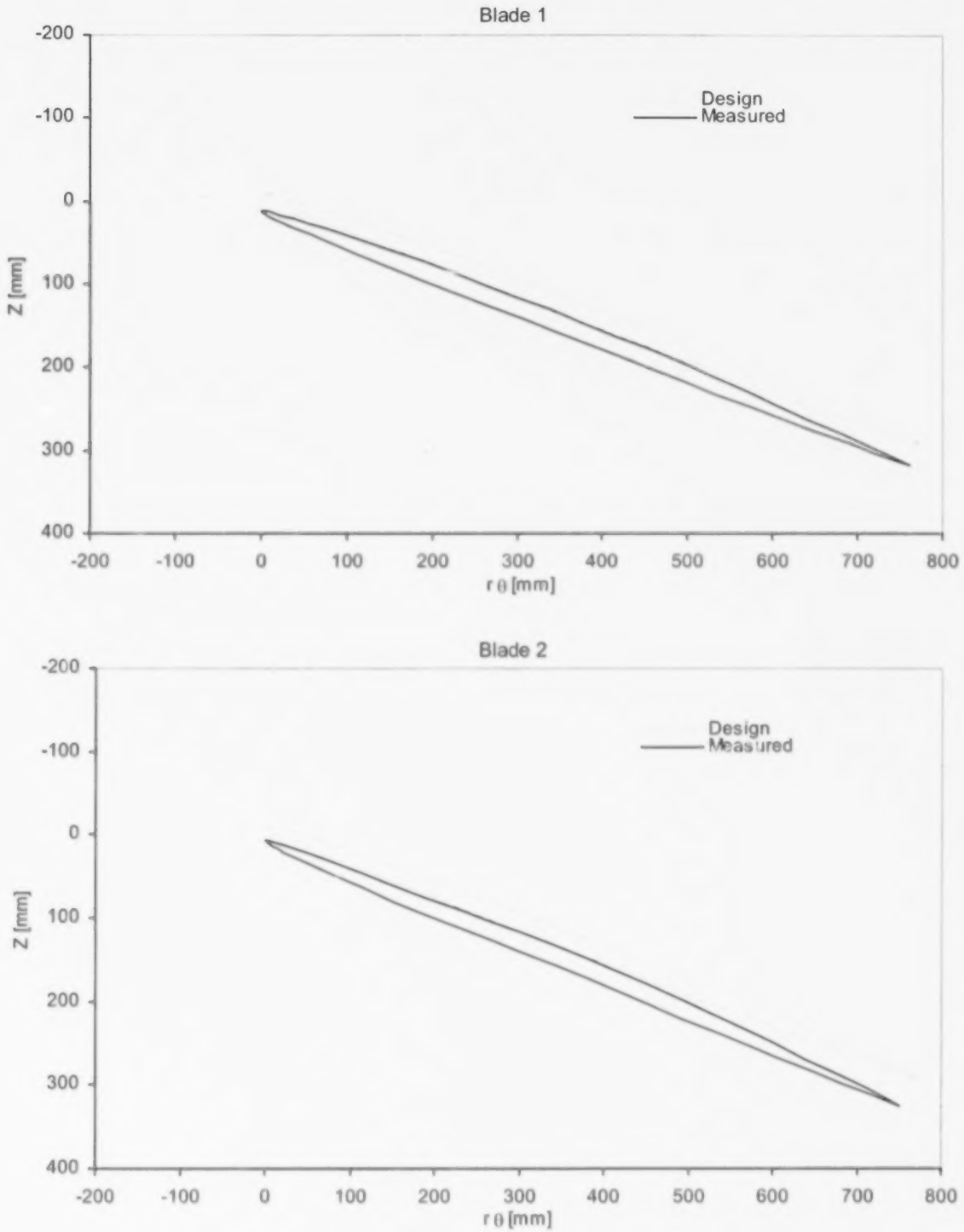


***Figure 24a**. Expanded Sections at a Radius Fraction of 0.95 for Blades 1 and 2 of the Port Propeller.*

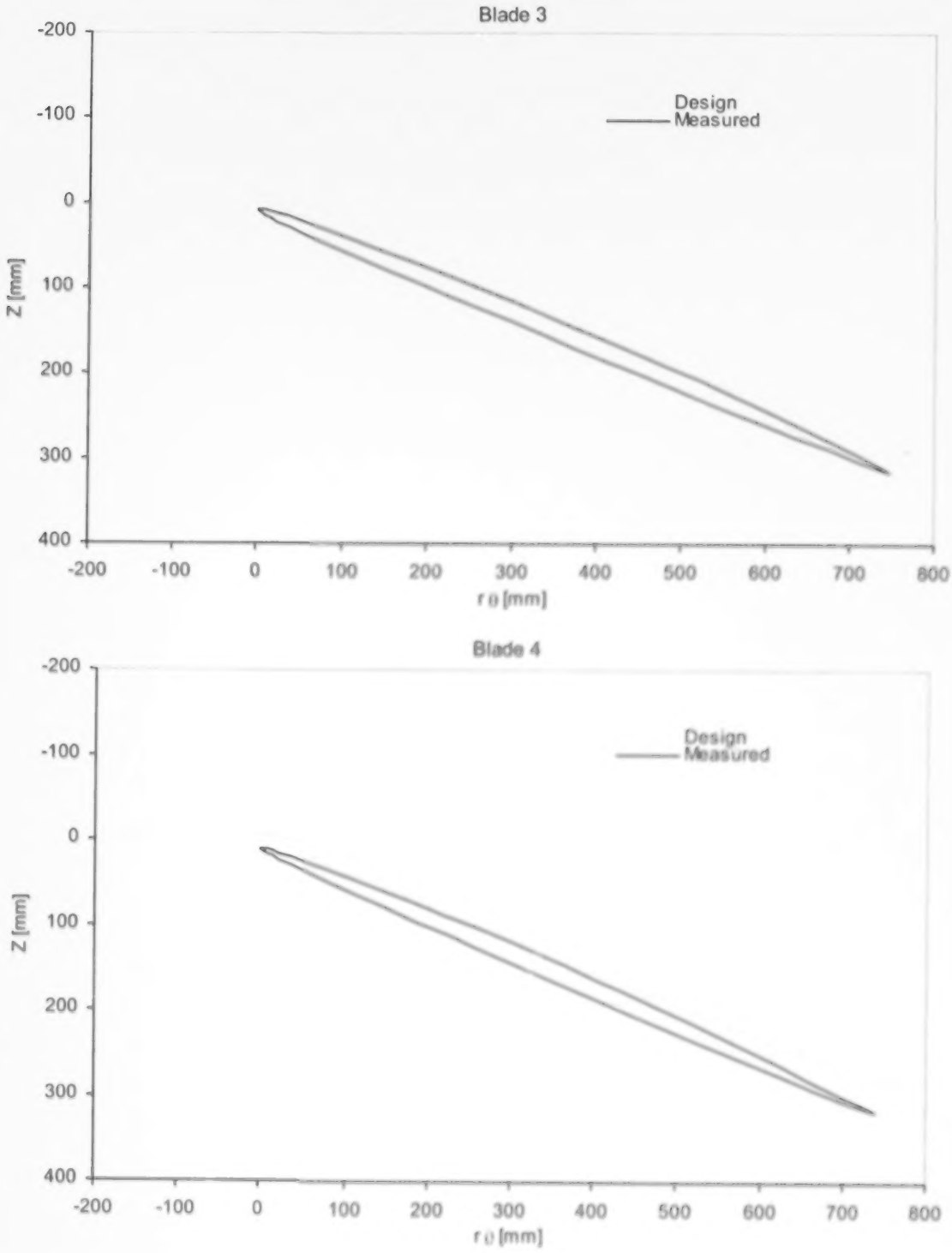


***Figure 24b**. Expanded Sections at a Radius Fraction of 0.95 for Blades 3 and 4 of the Port Propeller.*

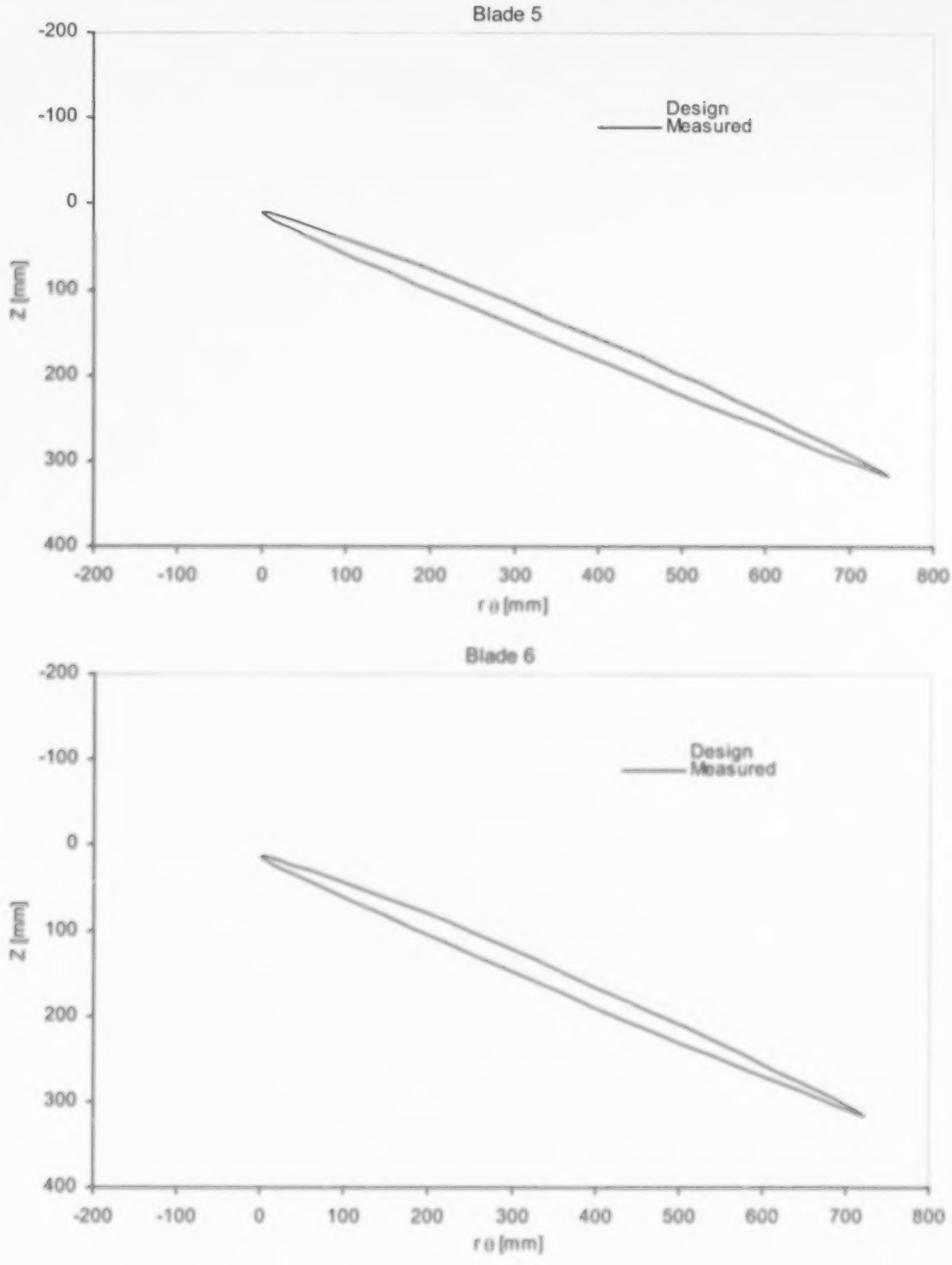


***Figure 24c**. Expanded Sections at a Radius Fraction of 0.95 for Blades 5 and 6 of the Port Propeller*

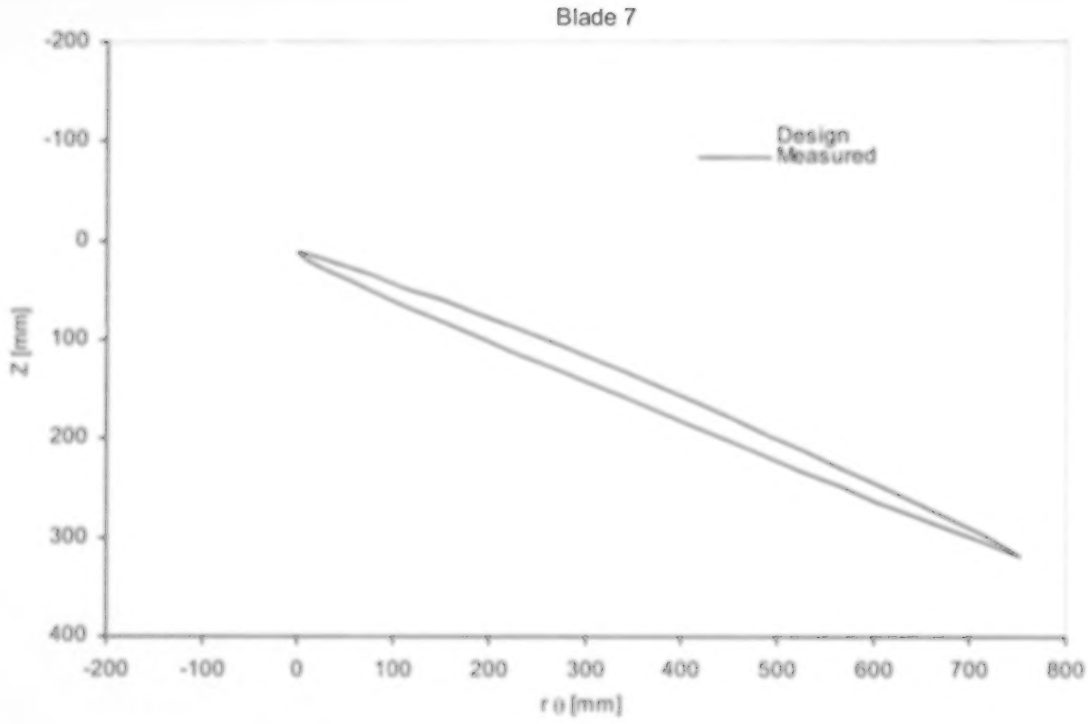


***Figure 24d**. Expanded Section at a Radius Fraction of 0.95 for Blade 7 of the Port Propeller.*

Figures 25a through 25d for blade sections at r/R = 0.90 of the port propeller continue to show the trend of decreasing over-pitch with decreasing radius with pitch angles increasing to a maximum of about 1.2 degrees above design on blade 6. Like sections at 95% of the tip radius, these sections all have decreases in chord length relative to design but to a lesser extent, reaching a maximum chord decrease of about 20 mm on blades 3, 4 and 5. As for sections at r/R = 0.95, these sections reach a maximum over-rake of more than 25 mm relative to design and show less blade-to-blade variation in local thickness than the sections at the outermost radius.

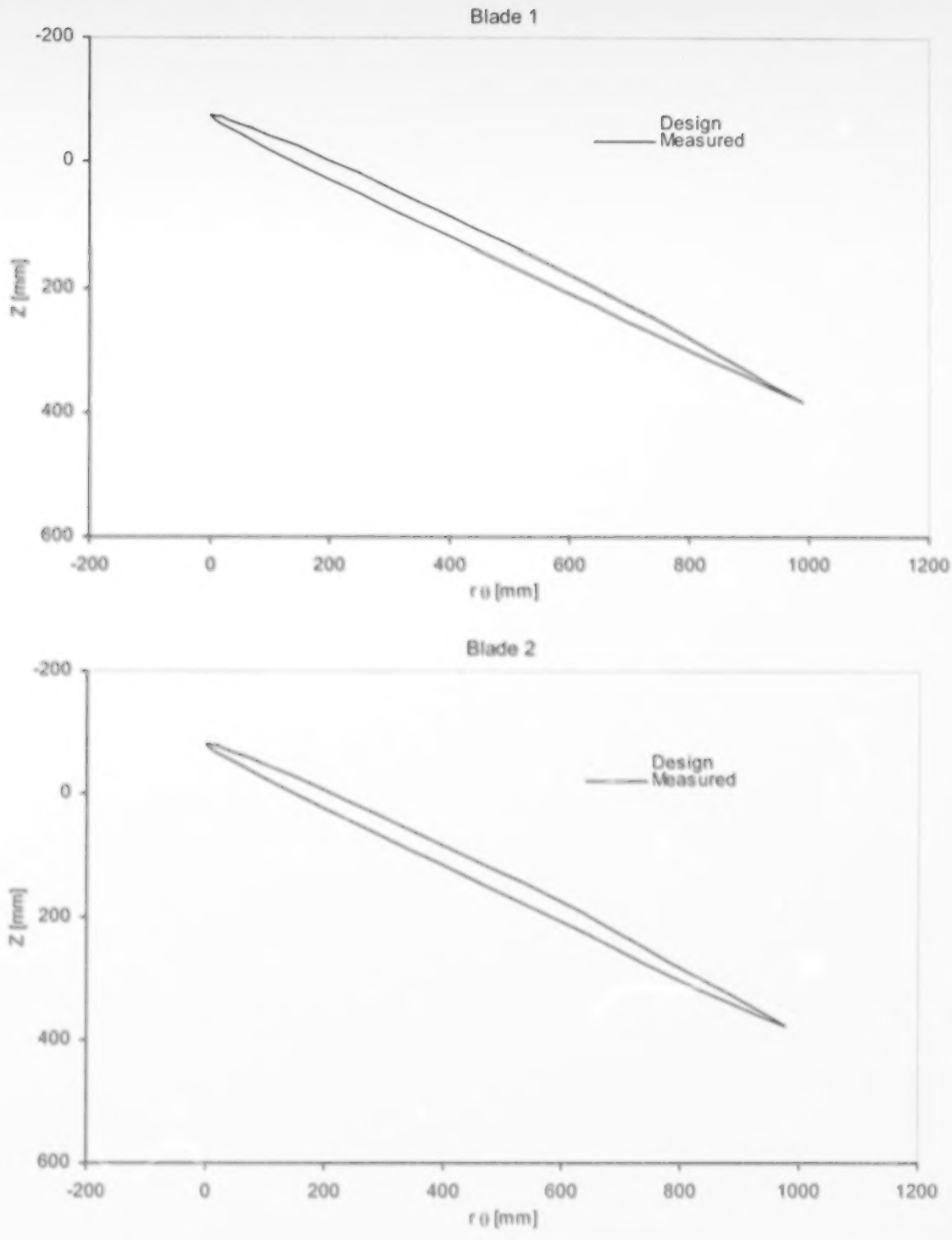


***Figure 25a**. Expanded Sections at a Radius Fraction of 0.90 for Blades 1 and 2 of the Port Propeller.*

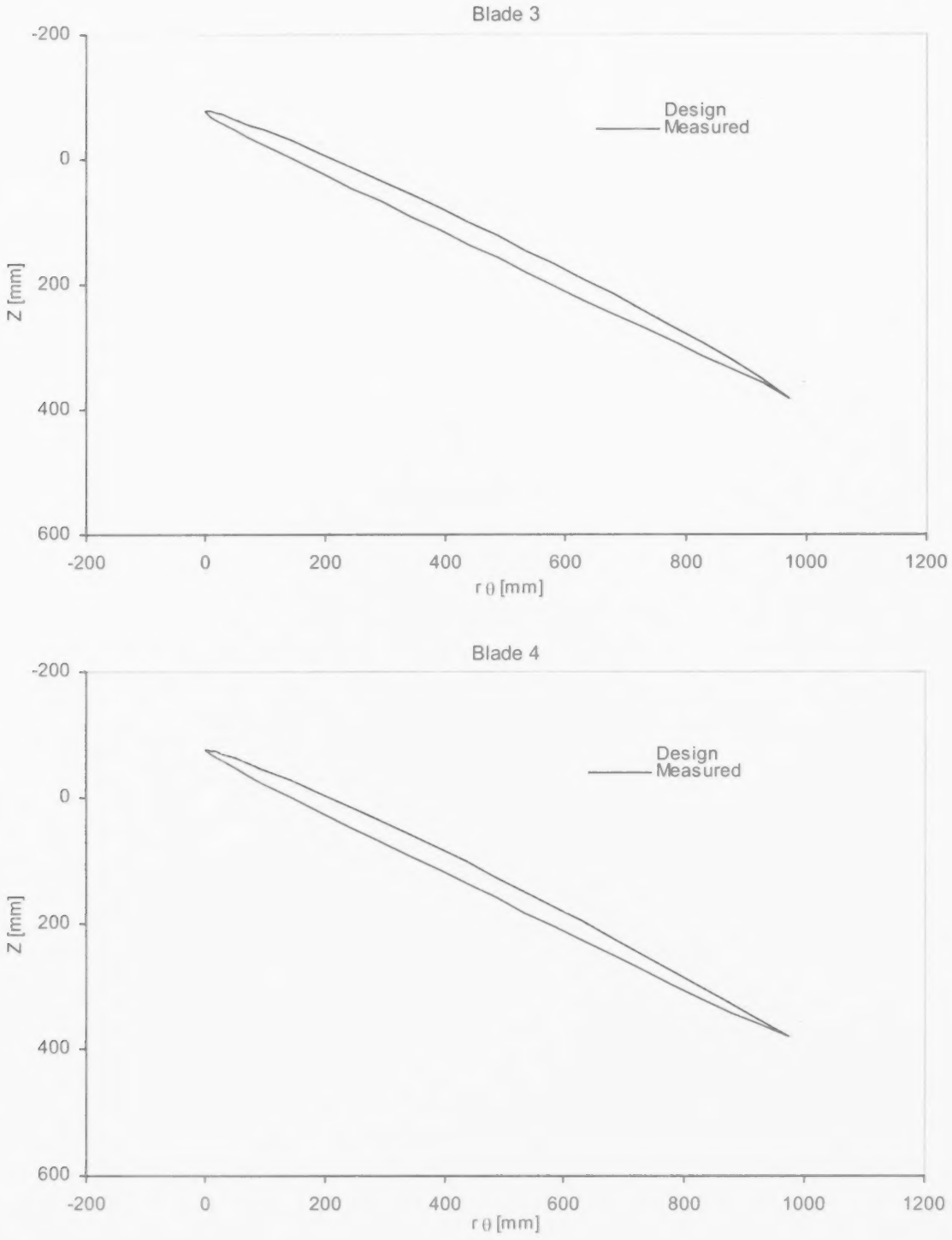


***Figure 25b**. Expanded Sections at a Radius Fraction of 0.90 for Blades 3 and 4 of the Port Propeller.*

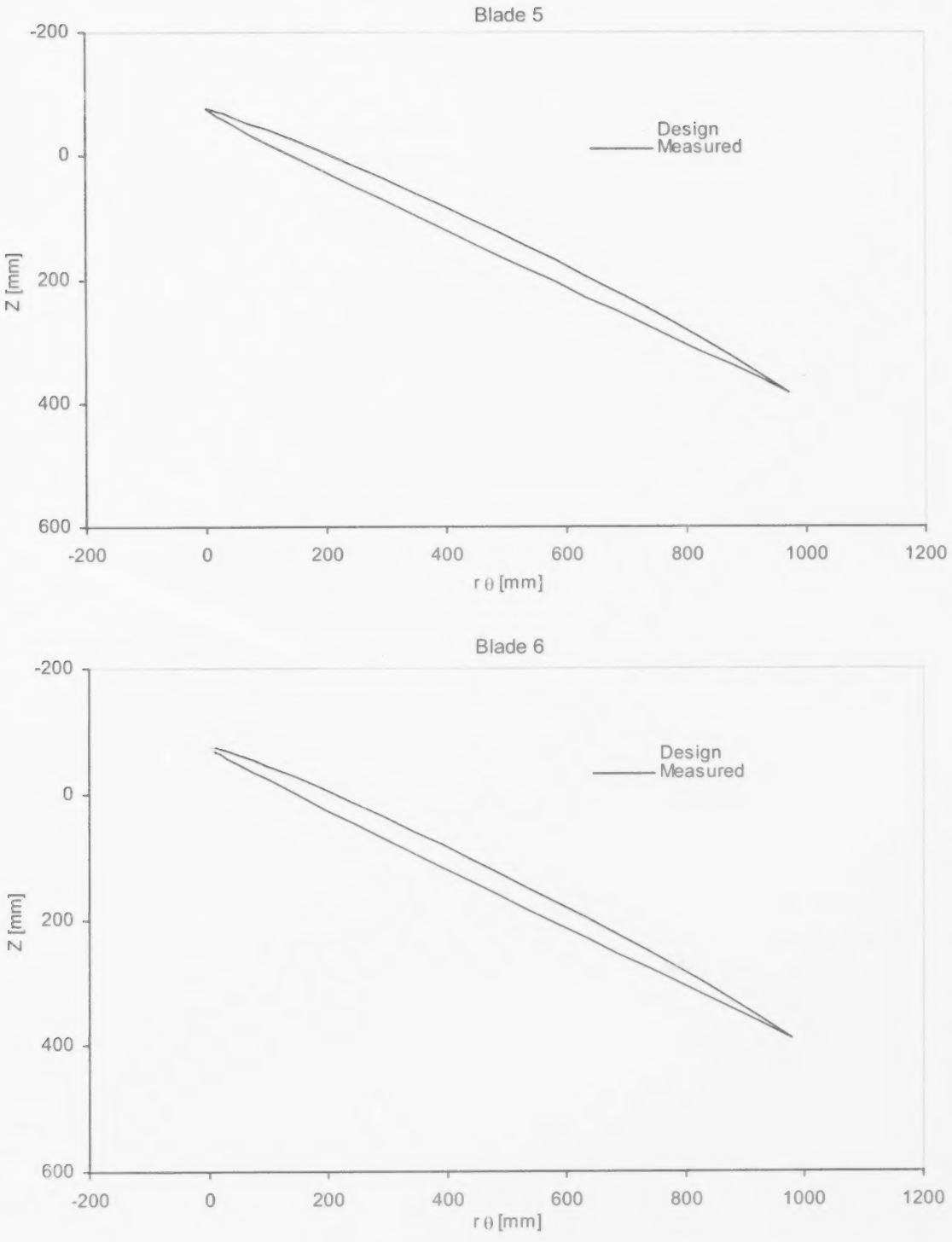


***Figure 25c**. Expanded Sections at a Radius Fraction of 0.90 for Blades 5 and 6 of the Port Propeller.*

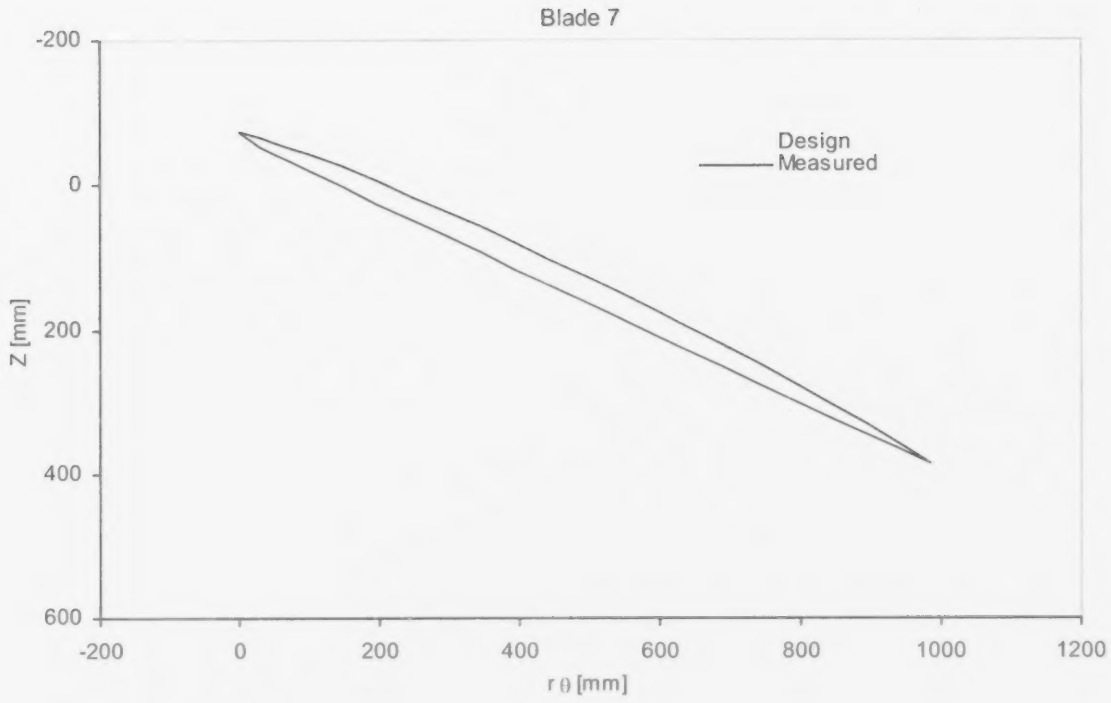


***Figure 25d**. Expanded Sections at a Radius Fraction of 0.90 for Blade 7 of the Port Propeller.*

Figures 26a through 26d for blade sections at r/R = 0.85 of the port propeller again continue the decrease of over-pitch with decreasing radius with pitch angles increasing by a maximum of about 1.0 degree above design on blade 6. Like sections at 90 and 95 percent of the tip radius, these sections all have decreases in chord length relative to design reaching a maximum chord decrease of about 19 mm on blades 2 and 4. These sections are over-raked by more than 20 mm relative to design on 5 of the 7 blades and show less blade-to-blade variation in local thickness than the sections at the outermost radius.

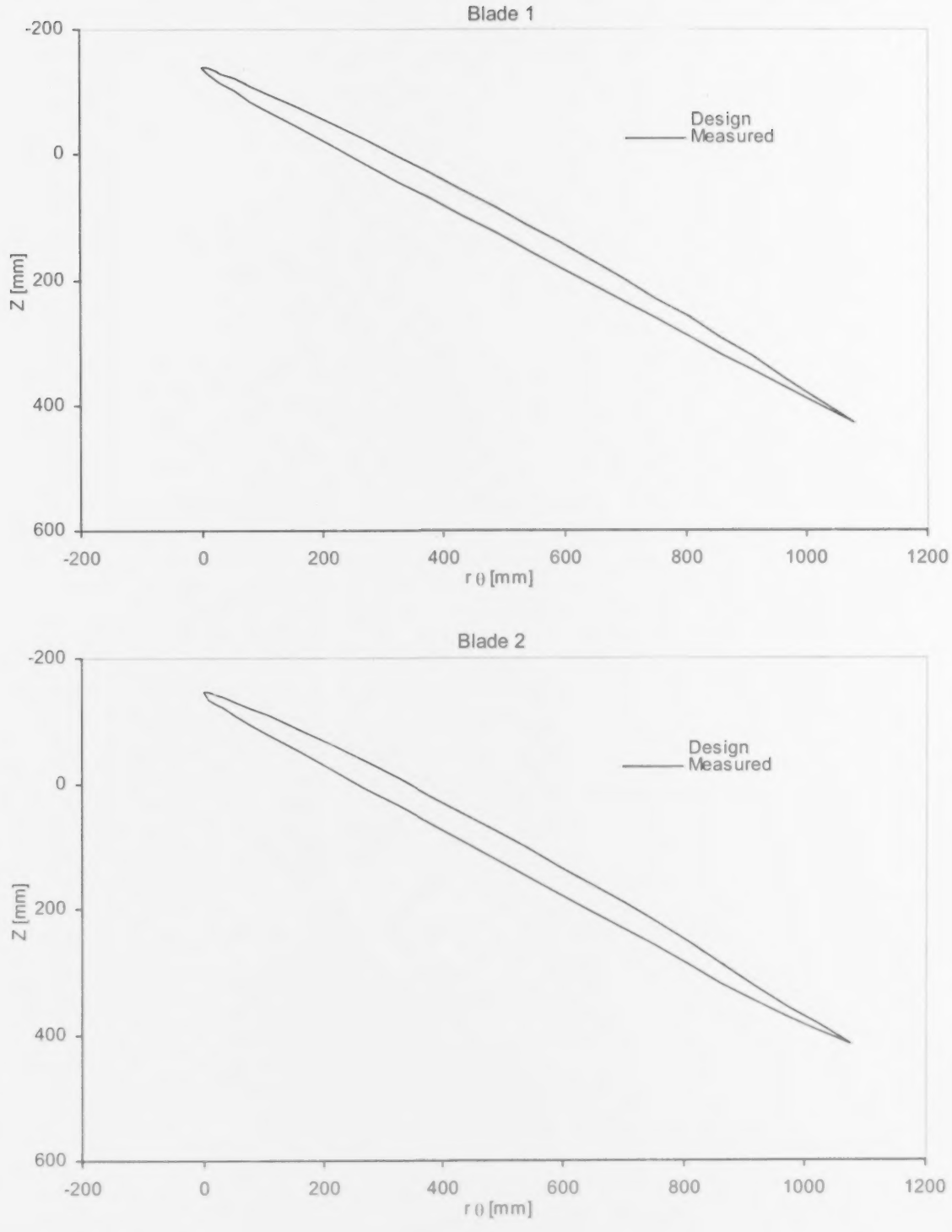


***Figure 26a**. Expanded Sections at a Radus Fraction of 0.85 for Blades 1 and 2 of the Port Propeller.*

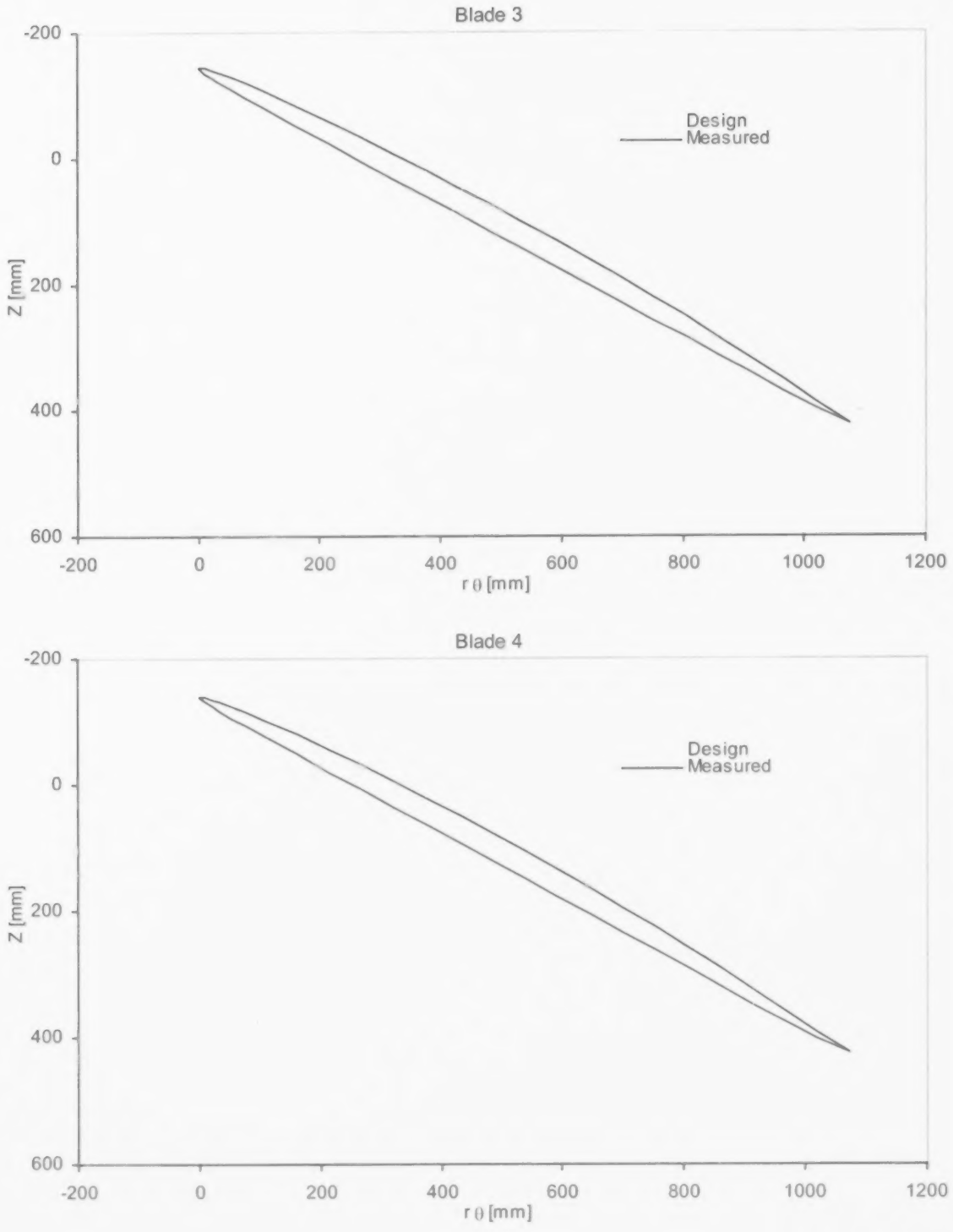
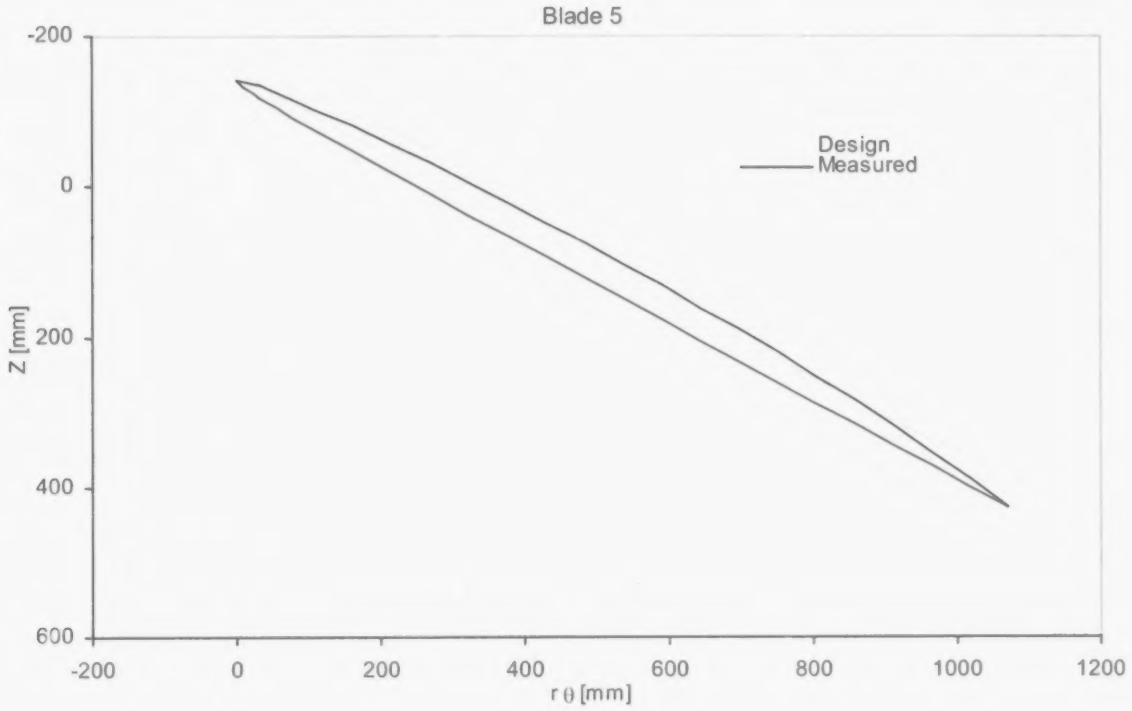
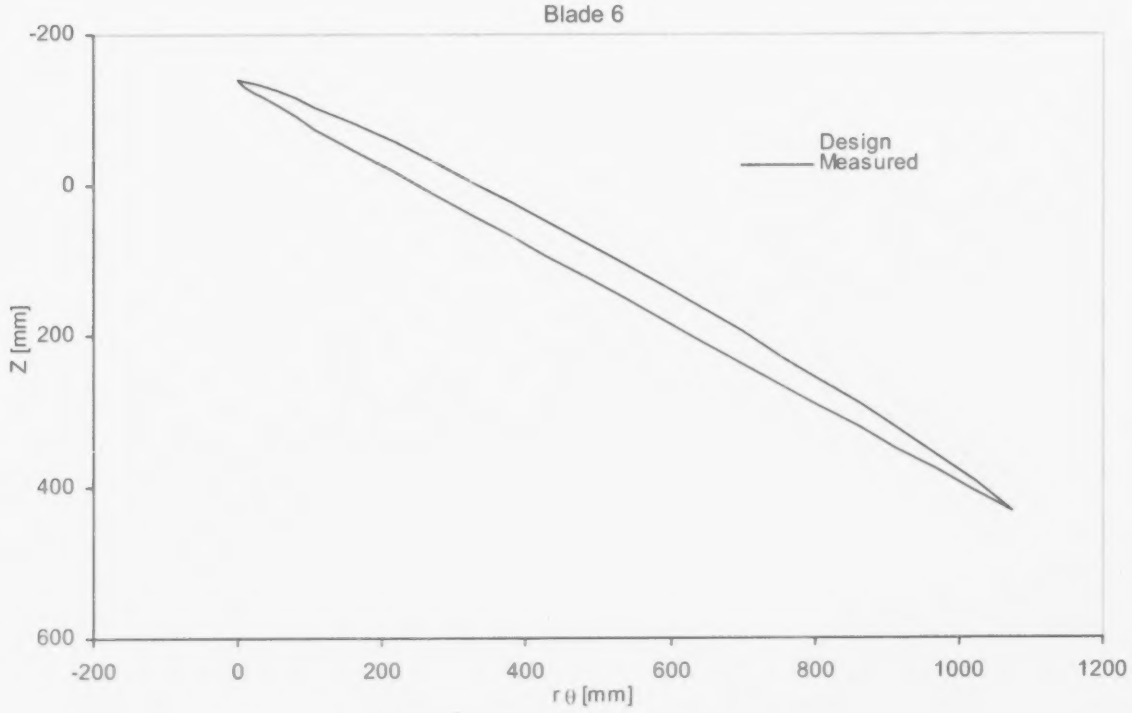


***Figure 26b**. Expanded Sections at a Radius Fraction of 0.85 for Blades 3 and 4 of the Port Propeller.*


Blade 5
-200
0
200
400
600
Z [mm]
Design
Measured
-200
0
200
400
600
800
1000
1200
r θ [mm]


Blade 6
-200
0
200
400
600
Z [mm]
Design
Measured
-200
0
200
400
600
800
1000
1200
r θ [mm]

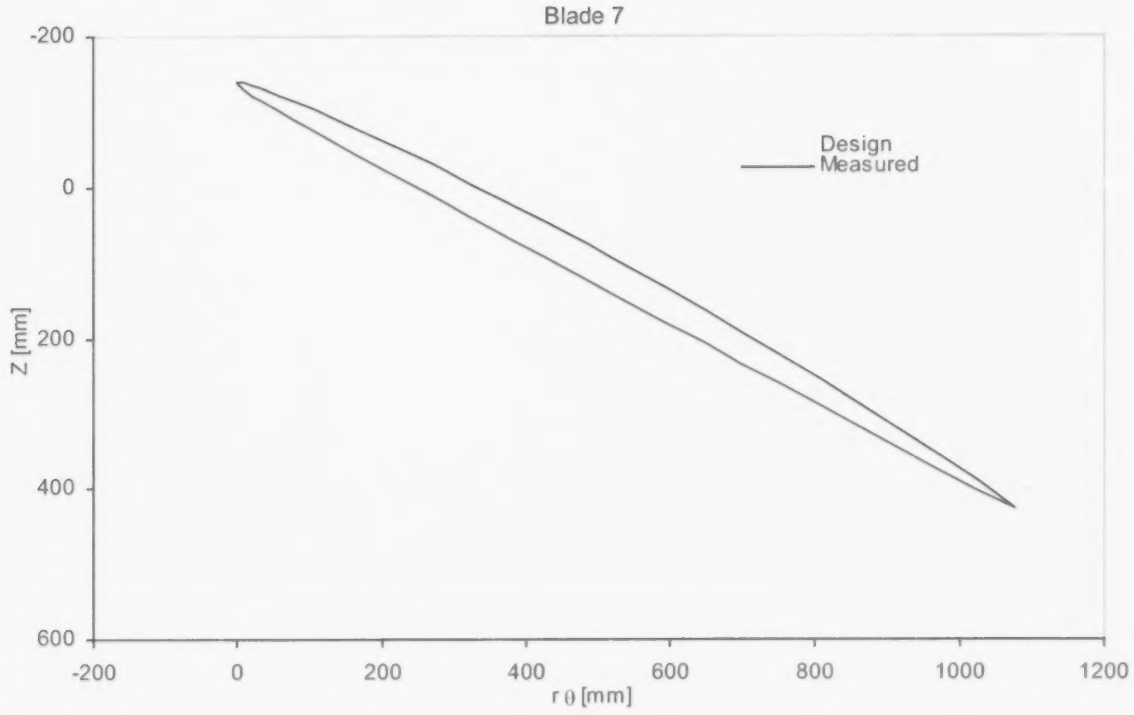


***Figure 26d**. Expanded Sections at a Radius Fraction of 0.85 for Blade 7 of the Port Propeller.*

Figures 27a through 27d for blade sections at r/R = 0.80 of the port propeller continue the decrease of over-pitch with decreasing radius with pitch angles increasing by a maximum of about 0.7 degrees above design on blade 6. Like sections between 85 and 95 percent of the tip radius, these sections all have decreases in chord length relative to design reaching a maximum chord decrease of about 13 mm on blade 2. These sections are over-raked by amounts ranging from 13 to 20 mm relative to design and show less blade-to-blade variation in local thickness than the sections at the outermost radius.

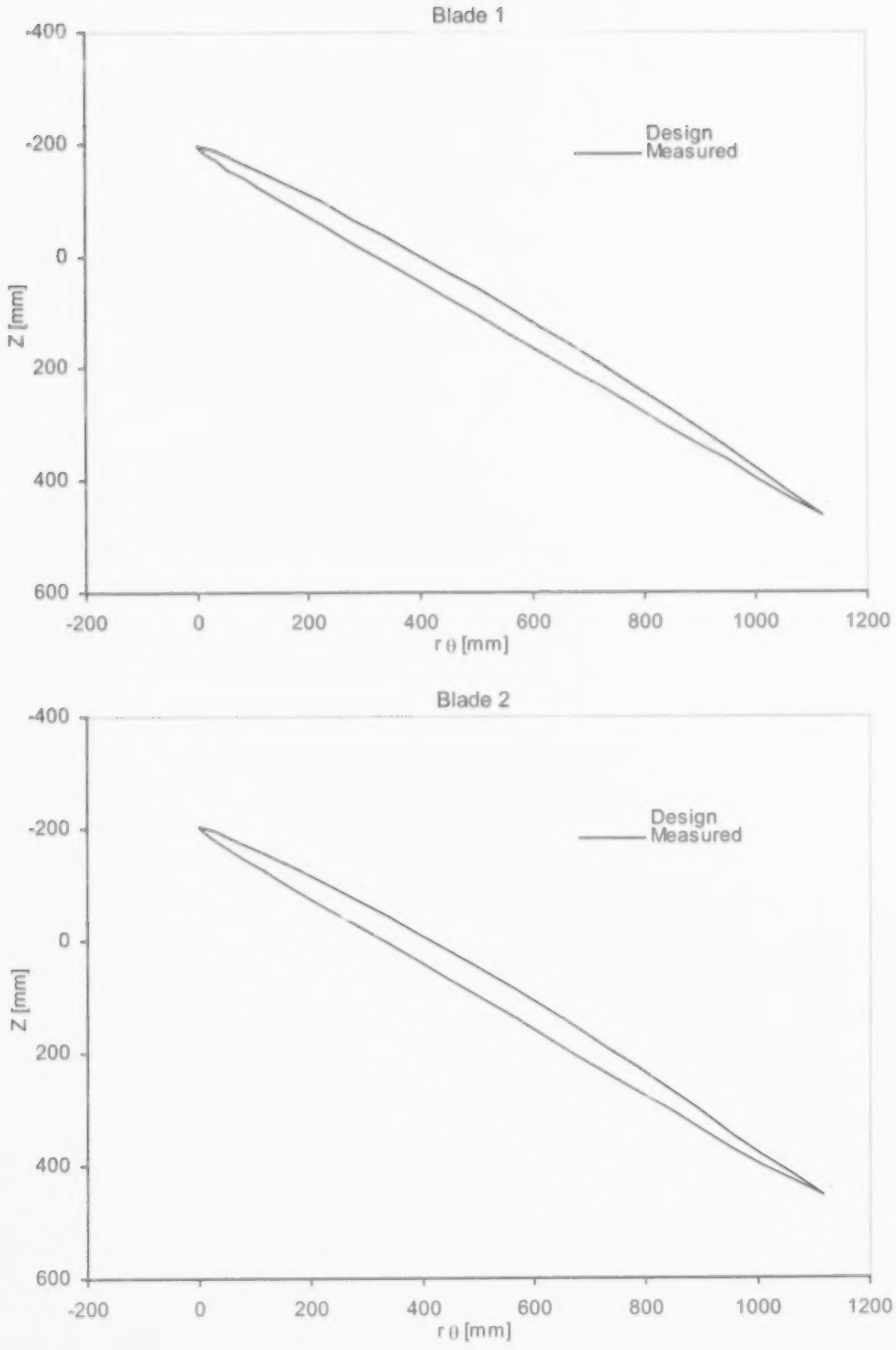


Figure 27a. *Expanded Sections at a Radius Fraction of 0.80 for Blades 1 and 2 of the Port Propeller*

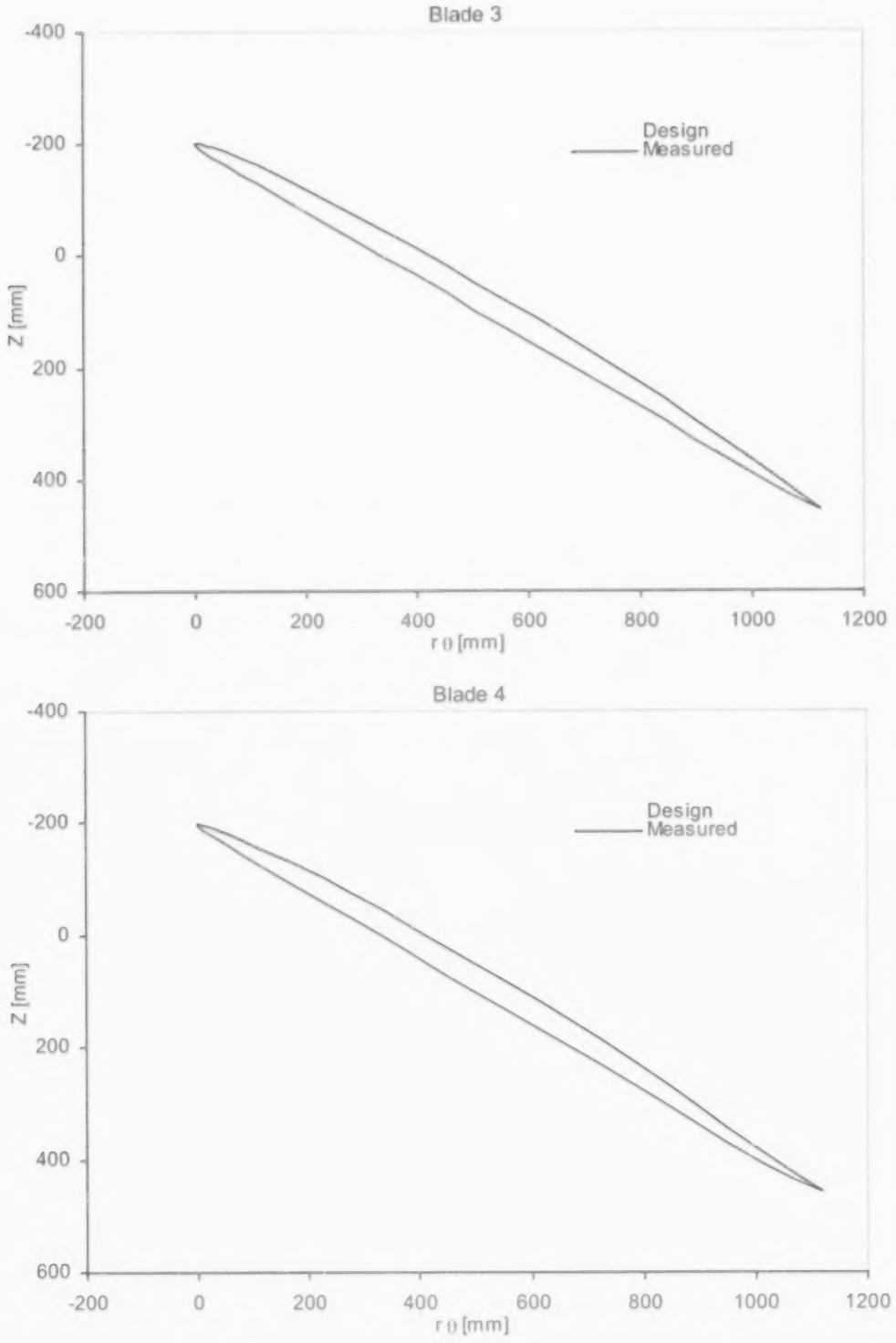
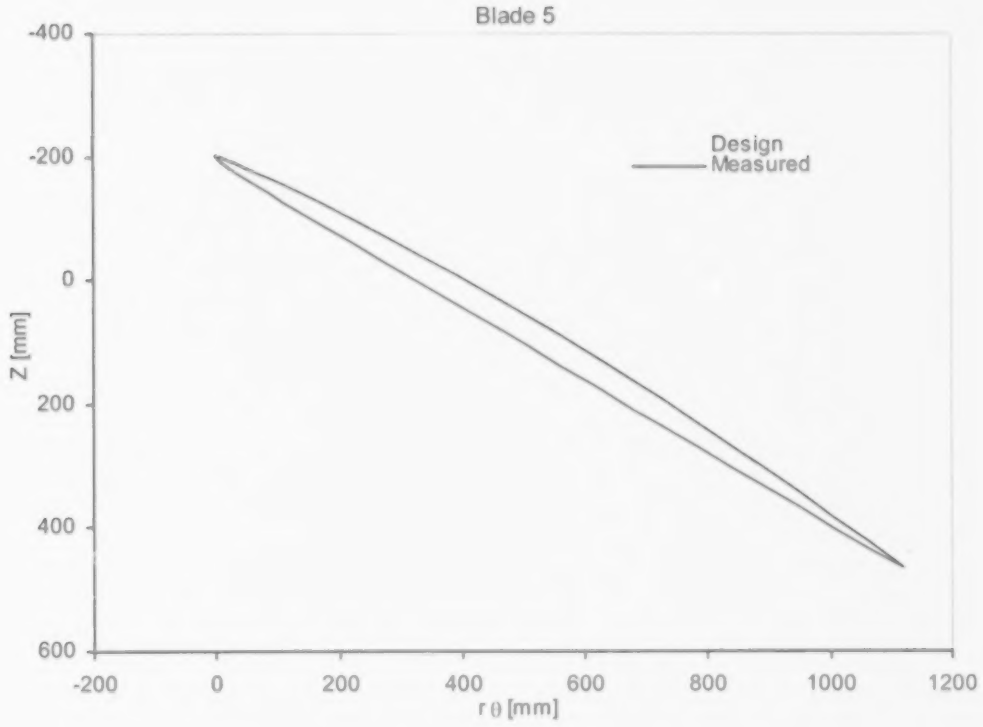
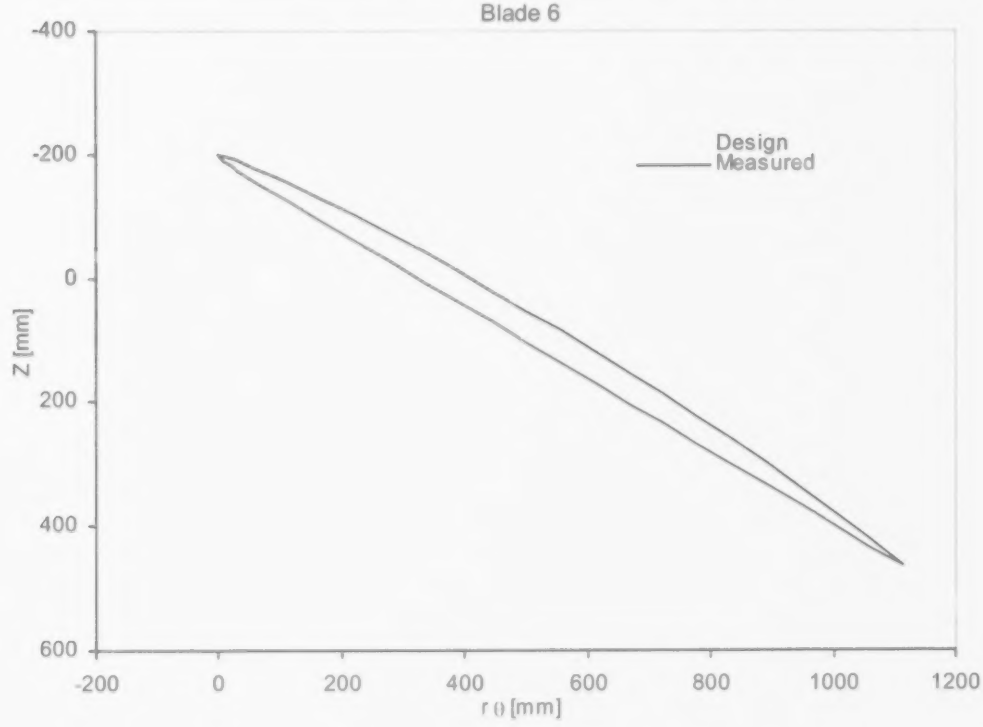


***Figure 27b**. Expanded Sections at a Radius Fraction of 0.80 for Blades 3 and 4 of the Port Propeller.*


Blade 5
-400
-200
0
200
400
600
Z [mm]
Design
Measured
-200
0
200
400
600
800
1000
1200
r θ [mm]


Blade 6
-400
-200
0
200
400
600
Z [mm]
Design
Measured
-200
0
200
400
600
800
1000
1200
r θ [mm]

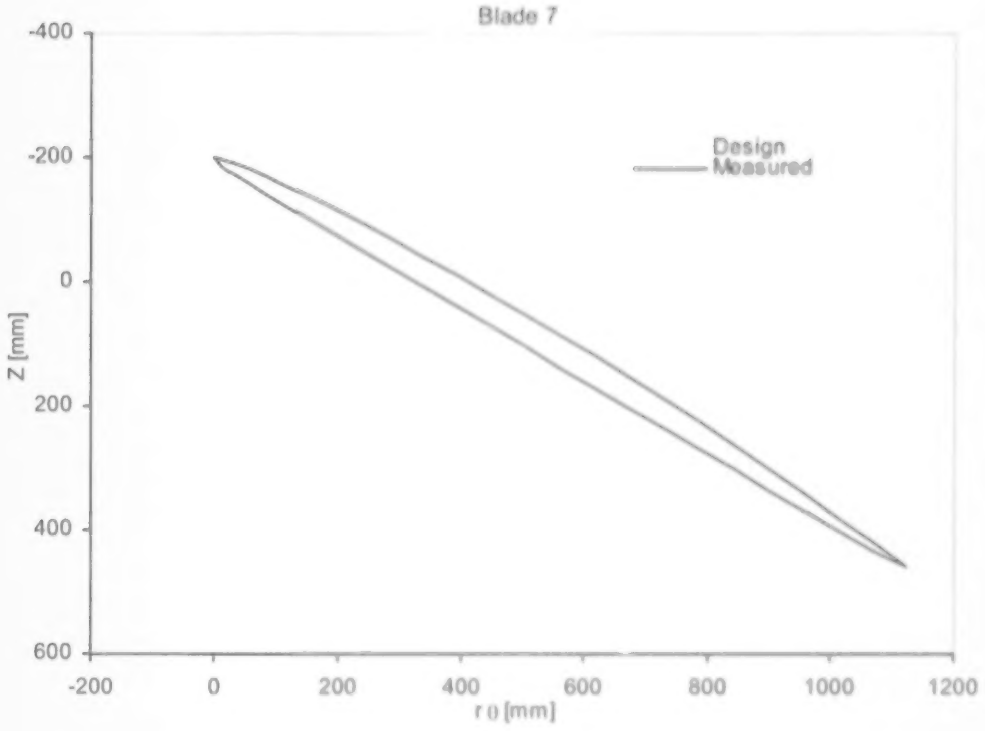


***Figure 27d**. Expanded Sections at a Radius Fraction of 0.80 for Blade 7 of the Port Propeller.*

Figures 28 through 32 compare the expanded views of measured sections of the starboard propeller blades to the corresponding design sections starting with the outermost sections on blades 1 through 7 at a radius fraction of 0.975 in Figures 28a through 28d and proceeding inboard in sequence to sections at a radius fraction of 0.80 in Figures 32a through 32d. The design sections are illustrated using a dashed line. The sections are drawn with leading edges on the right side of the figures to correspond to the orientation of the blades of the right-handed starboard propeller rotating outward in their top vertical reference position.

Figures 28a through 28d show the significant over-pitch of the outermost measured sections at r/R = 0.975 of the starboard propeller blades with pitch angles increasing to a maximum of about 1.8 degrees above design on blades 6 and 7. The inter-blade differences are much less and the leading edges are located much closer to design than for the outermost sections of the port propeller. These sections have significantly larger chord lengths than design reaching a maximum chord increase of about 62 mm on blade 2. The sections are also over-raked by 12 to 20 mm. The blade-to-blade variations in local thickness evident on the outermost sections of the port propeller are not as large for these sections but the local thickness of measured sections near their trailing edges is significantly larger than the design section. This may have been partly due to the significantly larger chord lengths.

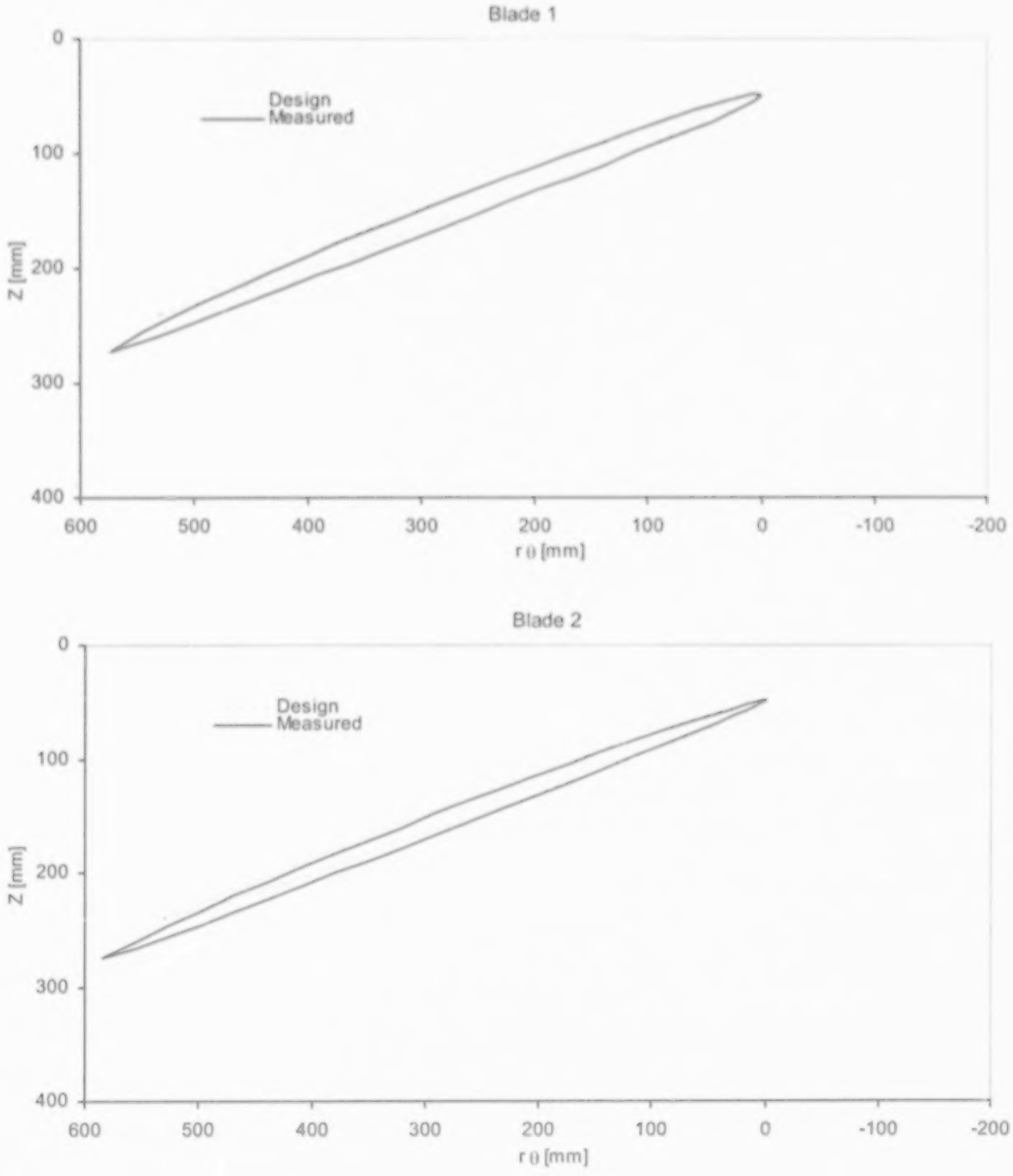


***Figure 28a**. Expanded Sections at a Radius Fraction of 0.975 for Blades 1 and 2 of the Starboard Propeller.*

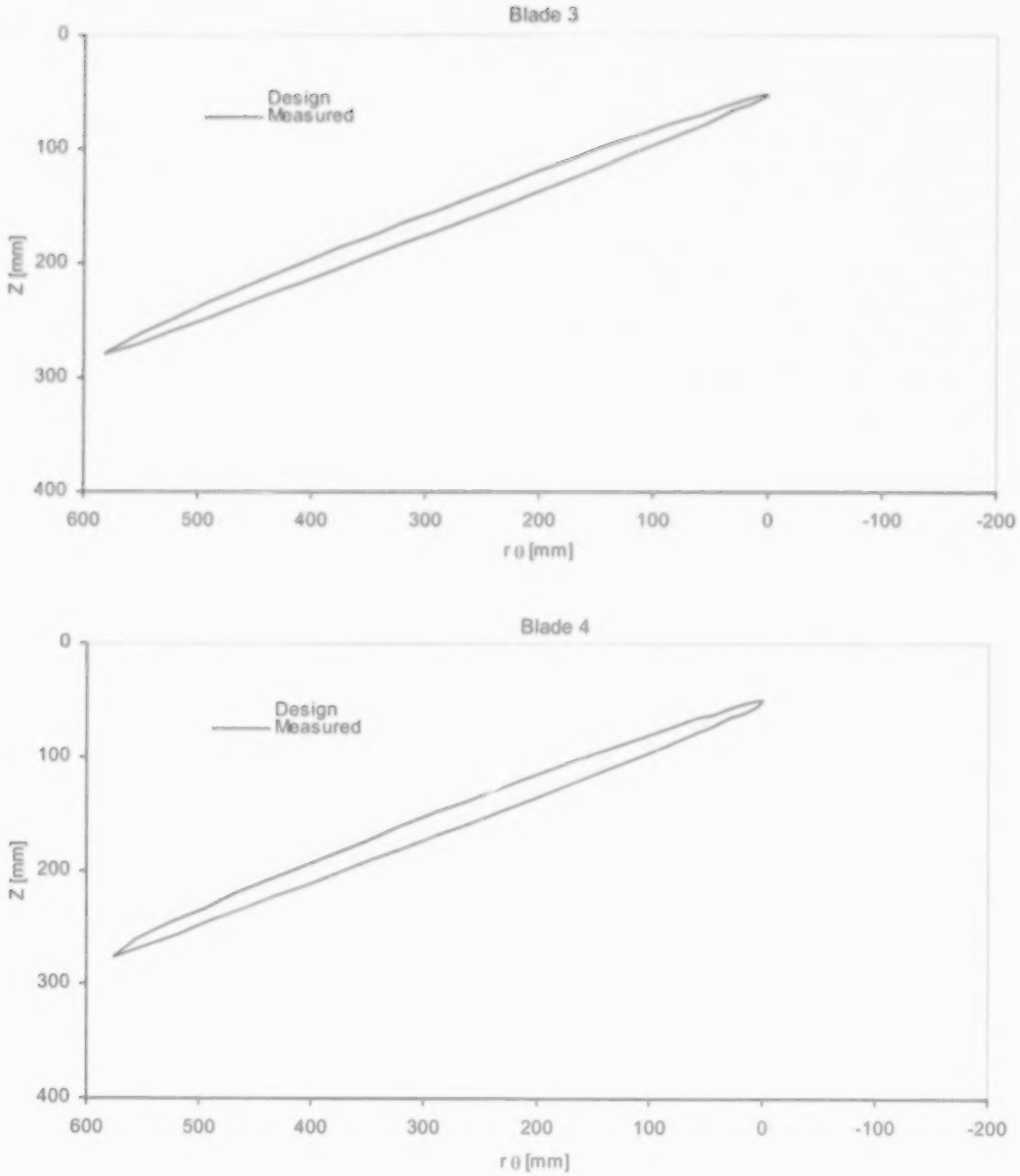


***Figure 28b**. Expanded Sections at a Radius Fraction of 0.975 for Blades 3 and 4 of the Starboard Propeller.*

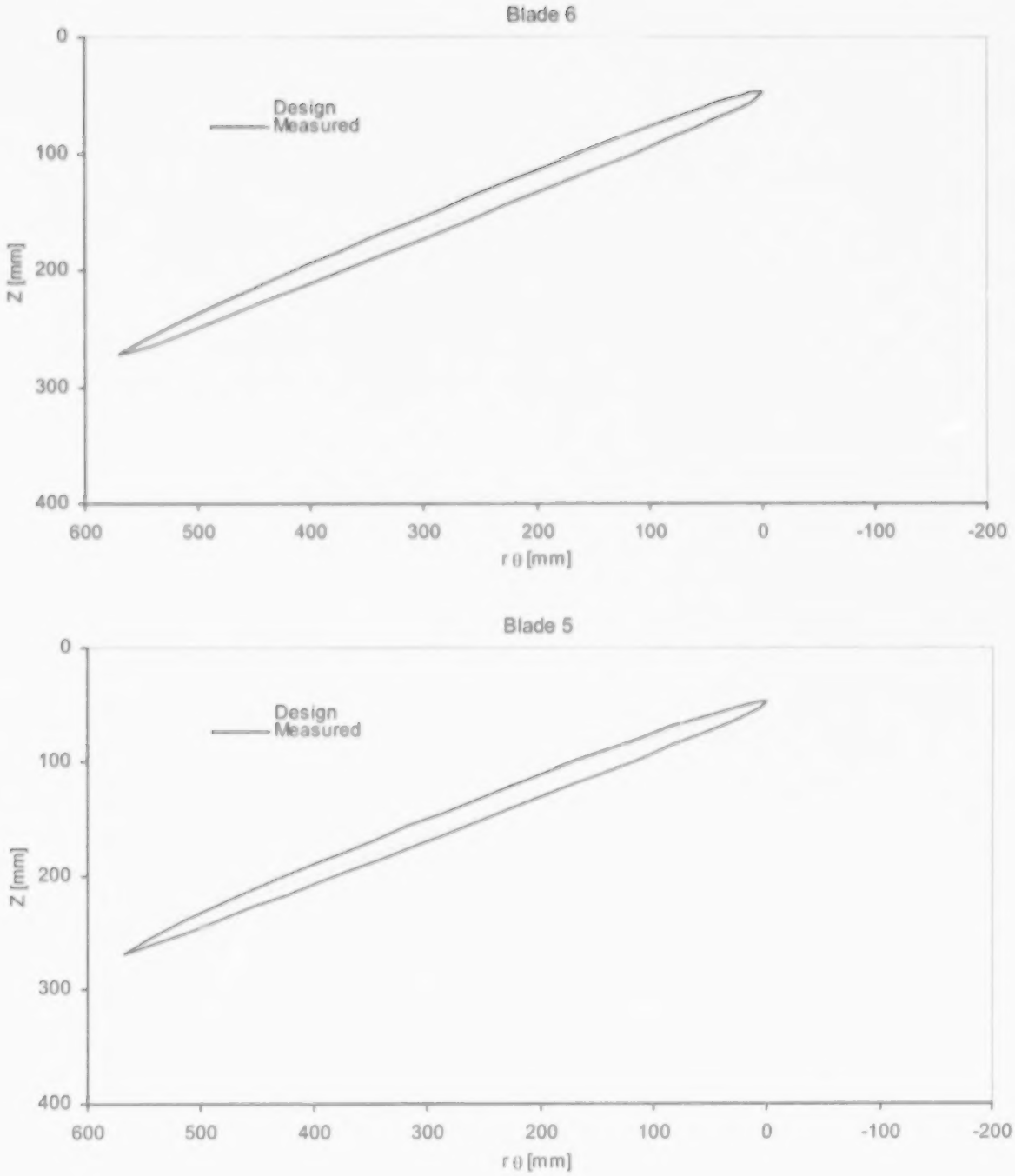


Figure 28c. *Expanded Sections at a Radius Fraction of 0.975 for Blades 5 and 6 of the Starboard Propeller.*

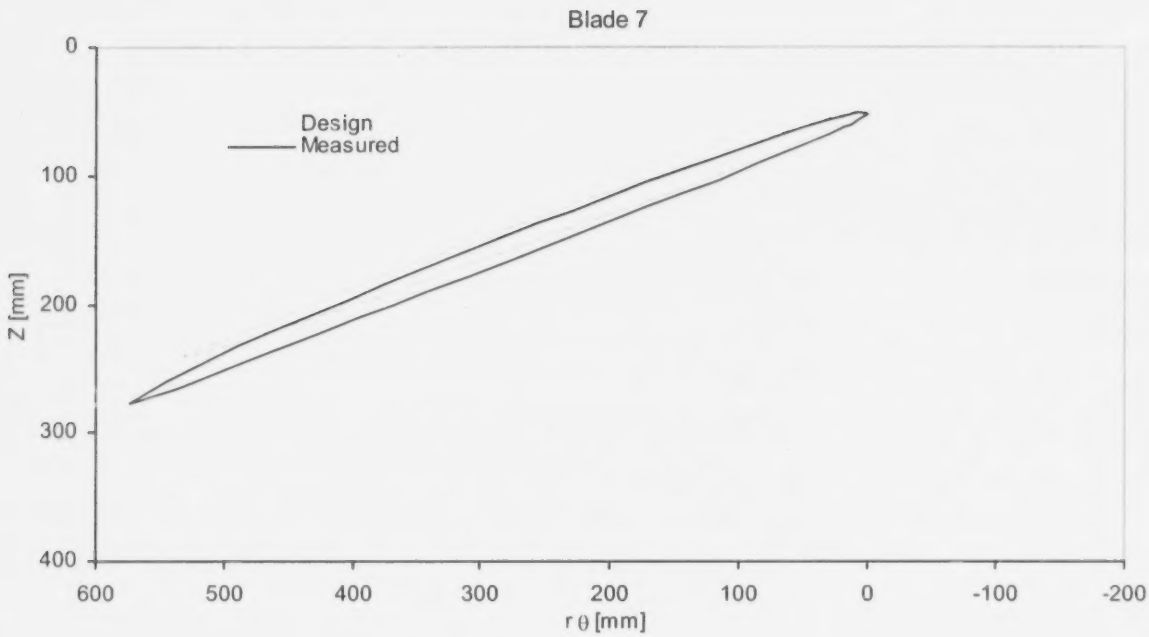


***Figure 28d**. Expanded Sections at a Radius Fraction of 0.975 for Blade 7 of the Starboard Propeller.*

Figures 29a through 29d for outer blade sections at r/R = 0.95 of the starboard propeller show slightly less over-pitch than the sections at r/R = 0.975 with pitch angles increasing to a maximum of about 1.2 degrees above design on blades 4 and 7. These sections have slight chord length variations ranging from 10 mm less than design on blade 1 to 14 mm greater than design on blade 2. As for sections at the outermost radius, these sections are all slightly over-raked with rake increases ranging from about 13 mm on blades 1 and 5 to 18 mm on blades 3 and 7. The blade-to-blade variations in local thickness evident on the outermost sections of the port propeller are not as significant for these sections.

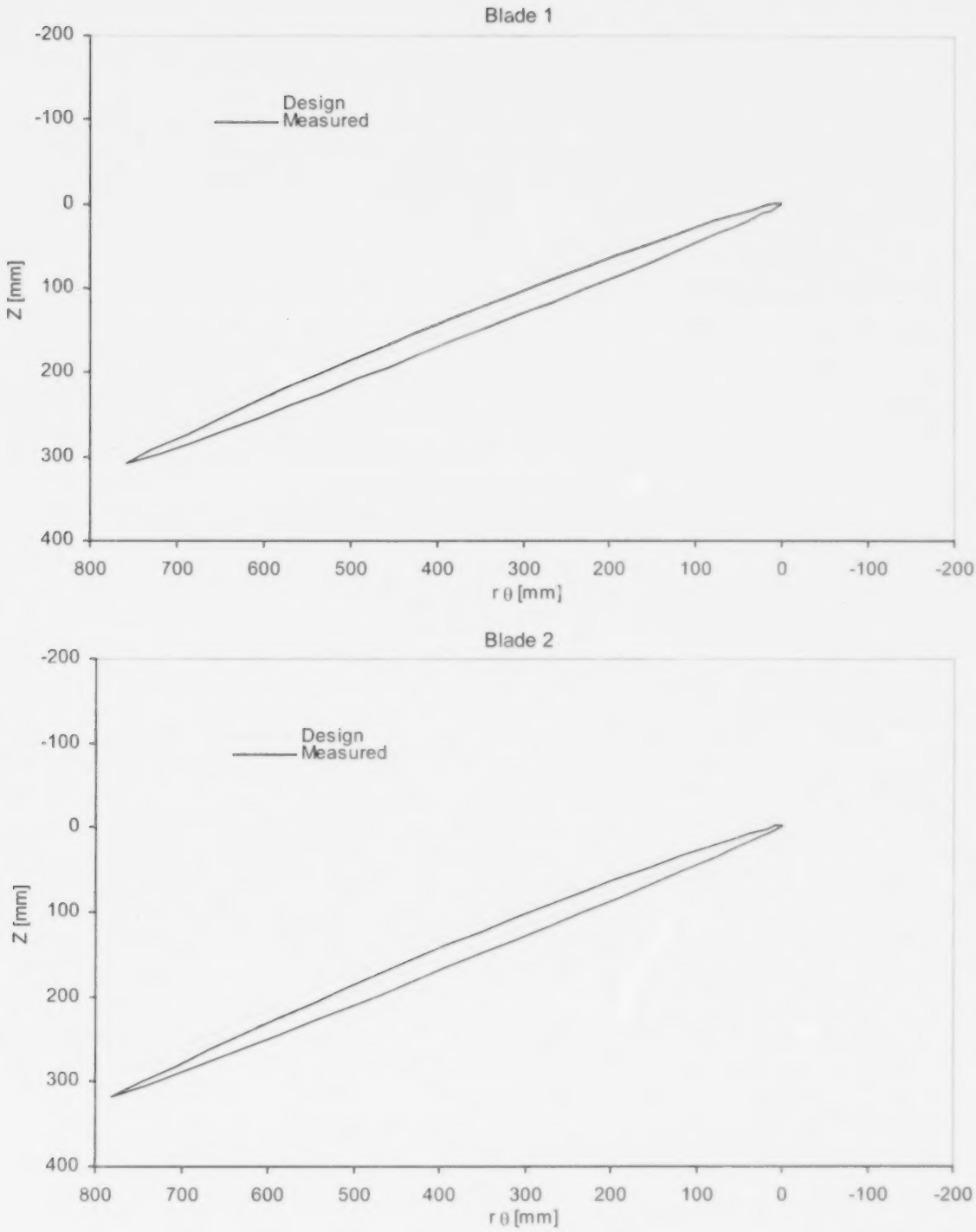


***Figure 29a**. Expanded Sections at a Radius Fraction of 0.95 for Blades 1 and 2 of the Starboard Propeller.*

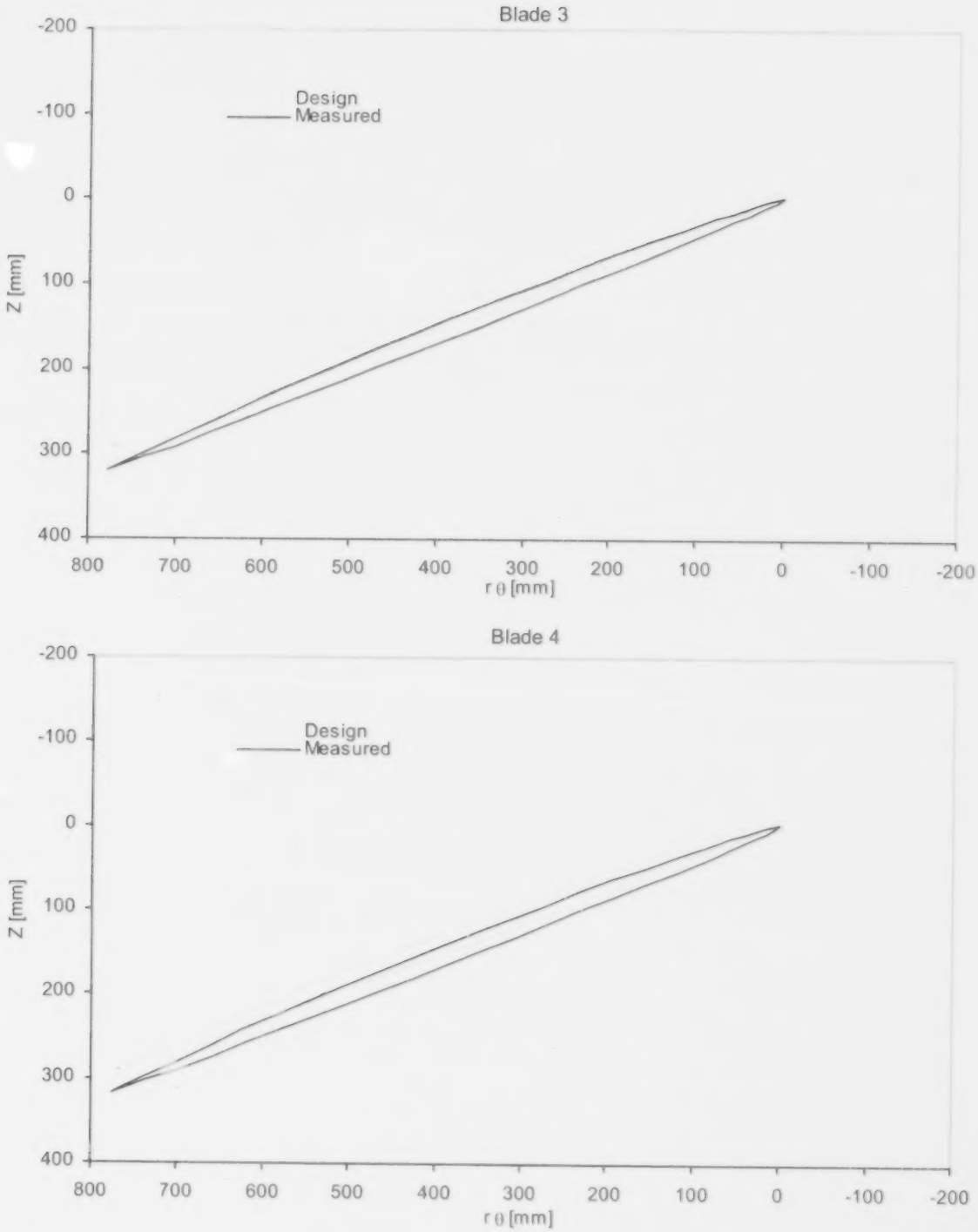


***Figure 29b**. Expanded Sections at a Radius Fraction of 0.95 for Blades 3 and 4 of the Starboard Propeller.*

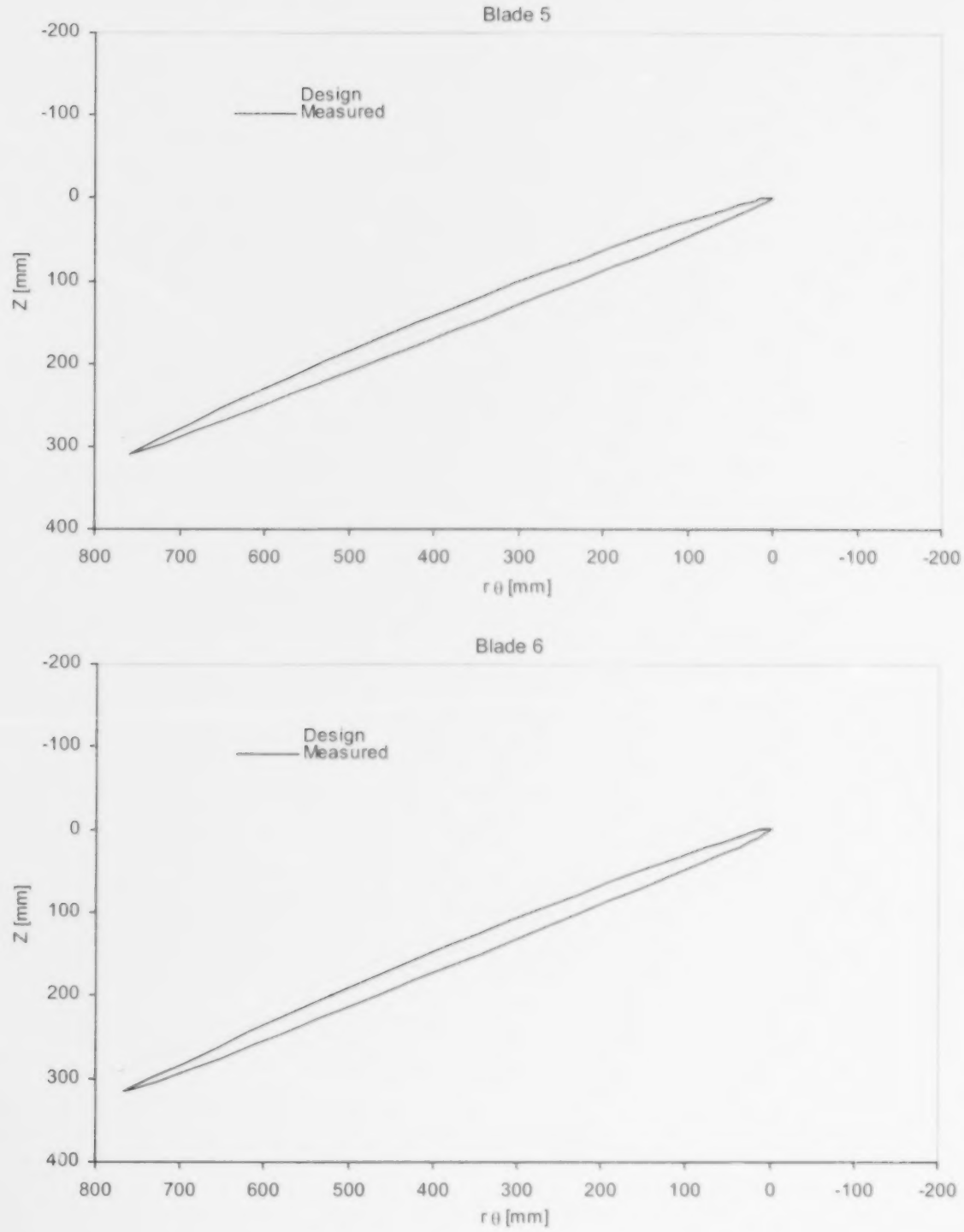


***Figure 29c**. Expanded Sections at a Radius Fraction of 0.95 for Blades 5 and 6 of the Starboard Propeller.*

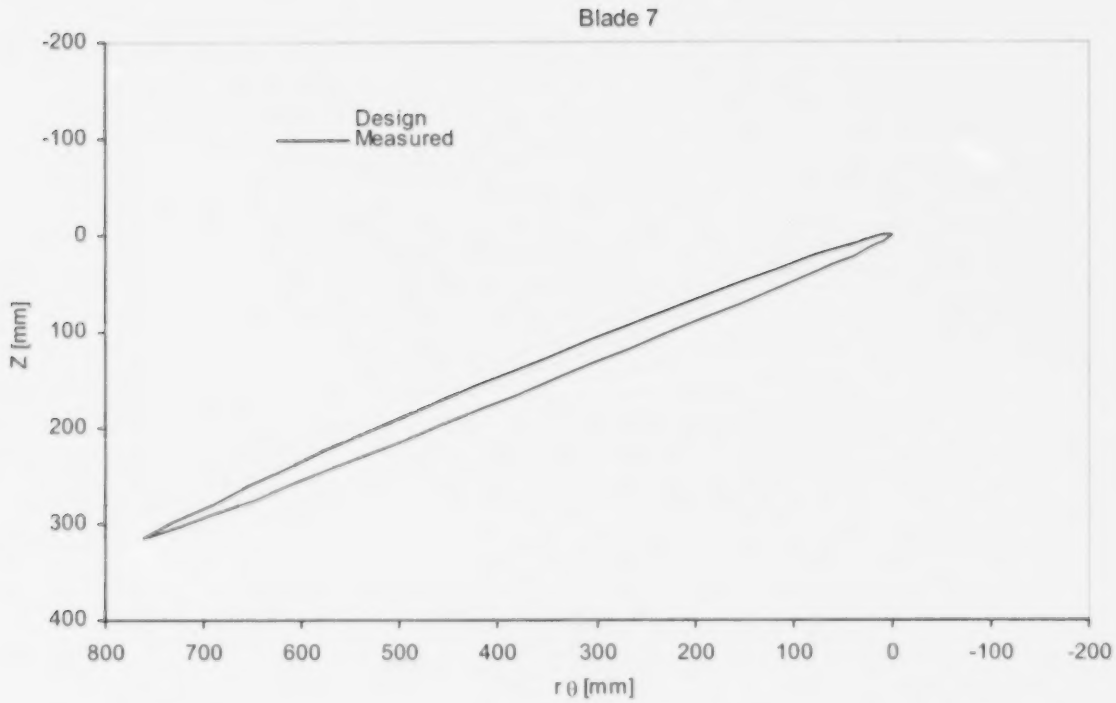


***Figure 29d**. Expanded Sections at a Radius Fraction of 0.95 for Blade 7 of the Starboard Propeller.*

Figures 30a through 30d for blade sections at r/R = 0.90 of the starboard propeller continue to show slight decreases in over-pitch with decreasing radius with pitch angles all less that one degree larger than design. These sections have slight chord length variations ranging from 17 mm less than design on blade 5 to 3 mm greater than design on blade 2. As for sections at larger radii, these sections are all slightly over-raked with rake increases ranging from about 12 mm on blade 6 to 20 mm on blade 7 and the blade-to-blade variations in local thickness are not significant for these sections.

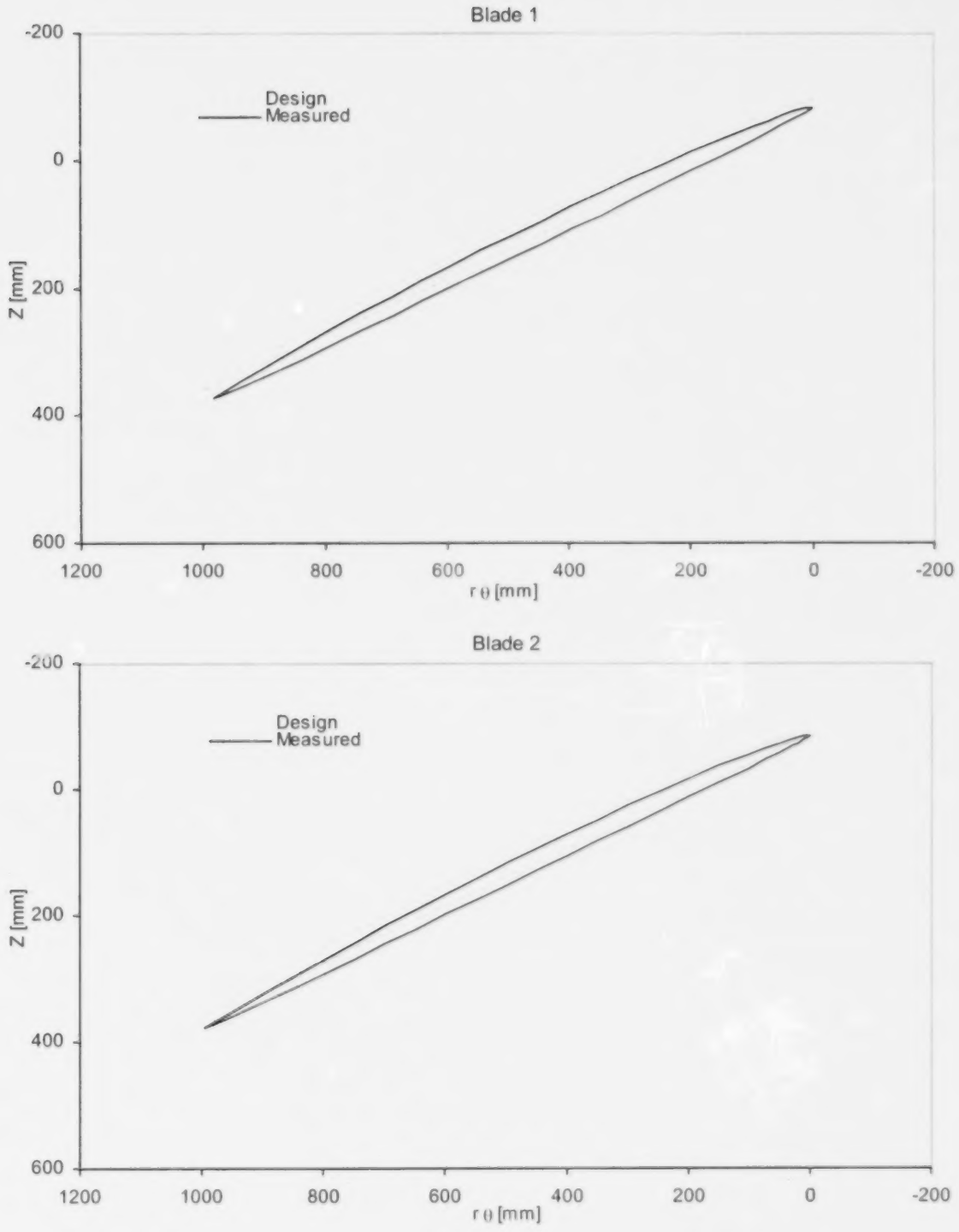


***Figure 30a**. Expanded Sections at a Radius Fraction of 0.90 for Blades 1 and 2 of the Starboard Propeller.*

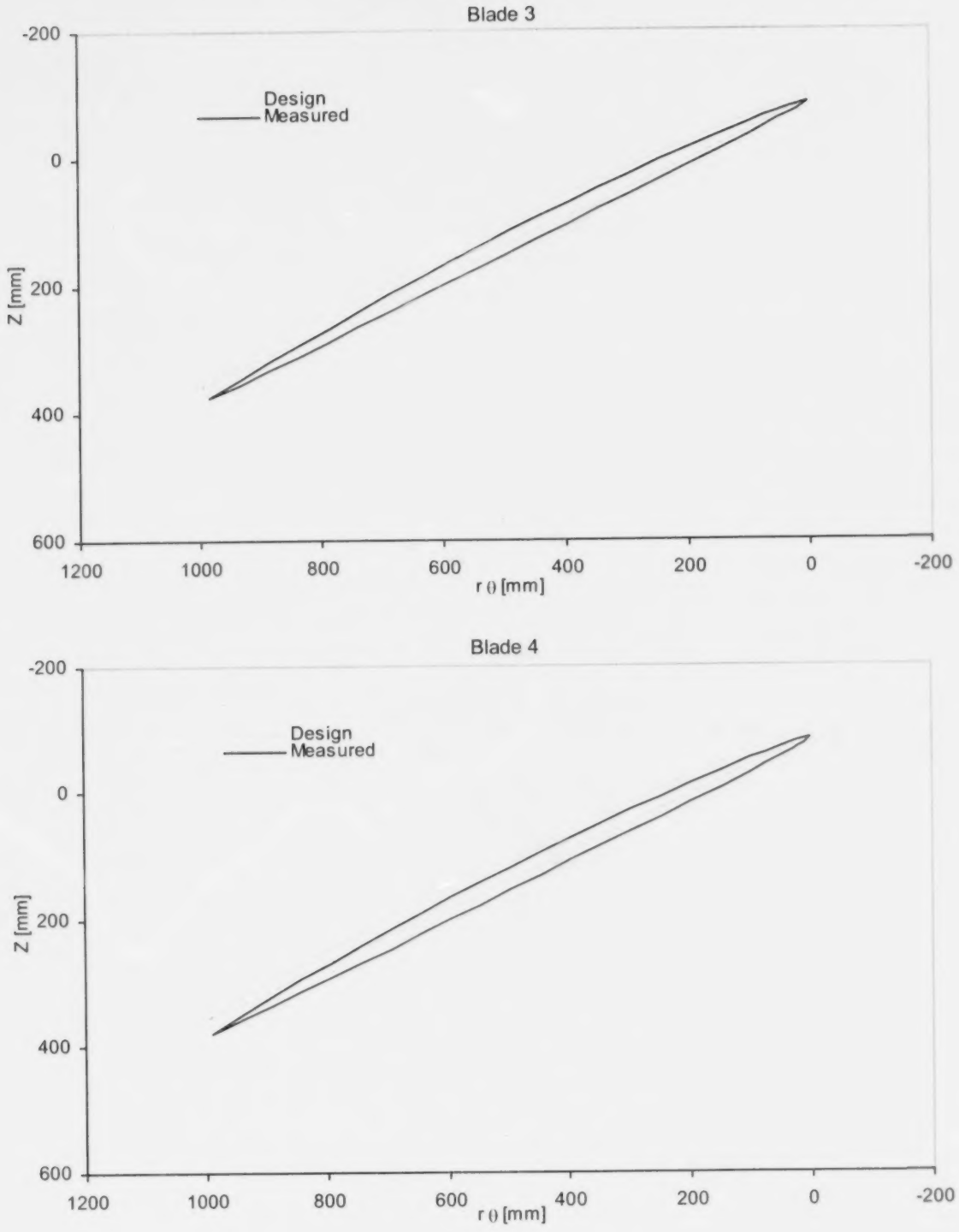


***Figure 30b**. Expanded Sections at a Radius Fraction of 0.90 for Blades 3 and 4 of the Starboard Propeller.*

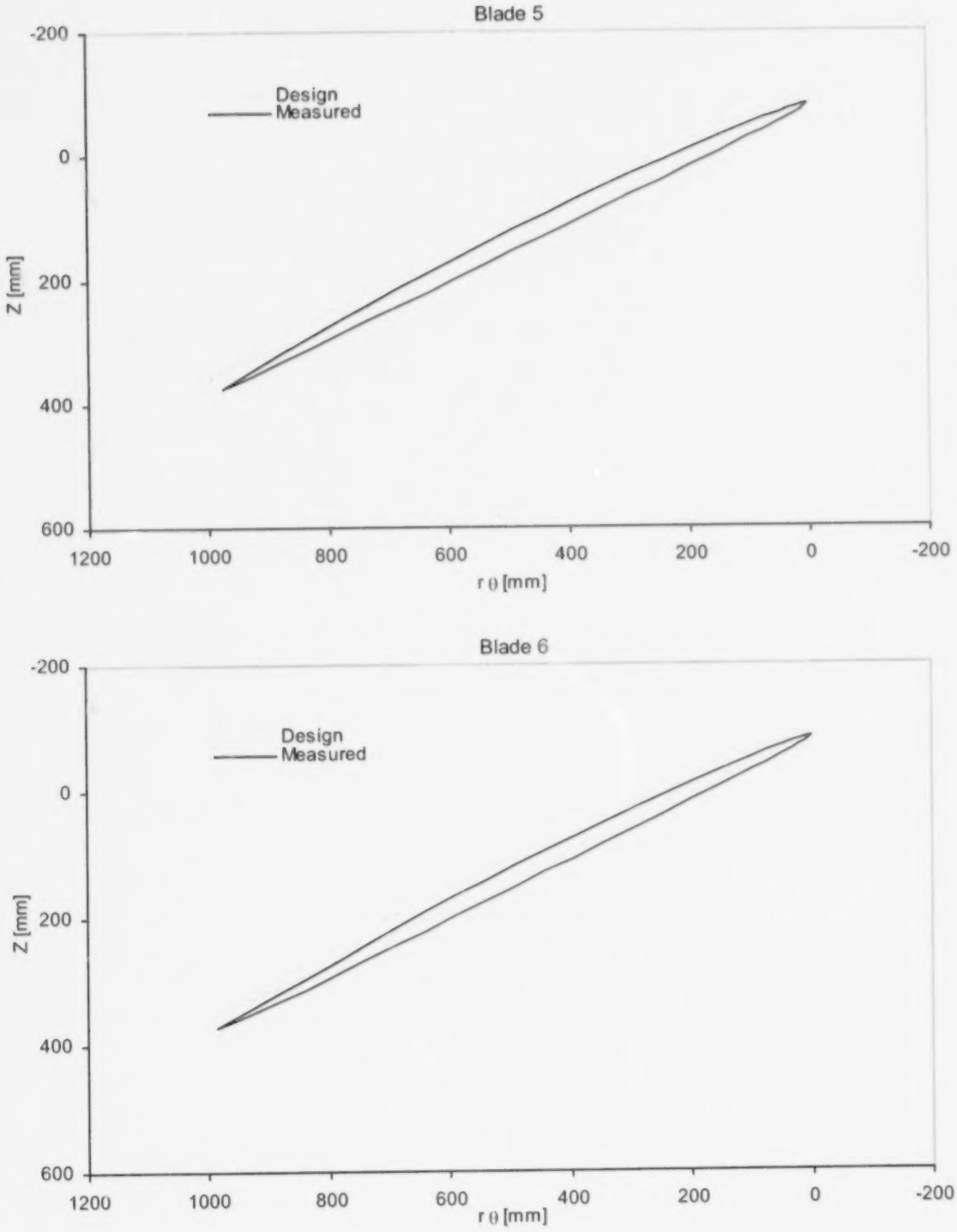


***Figure 30c**. Expanded Sections at a Radius Fraction of 0.90 for Blades 5 and 6 of the Starboard Propeller.*

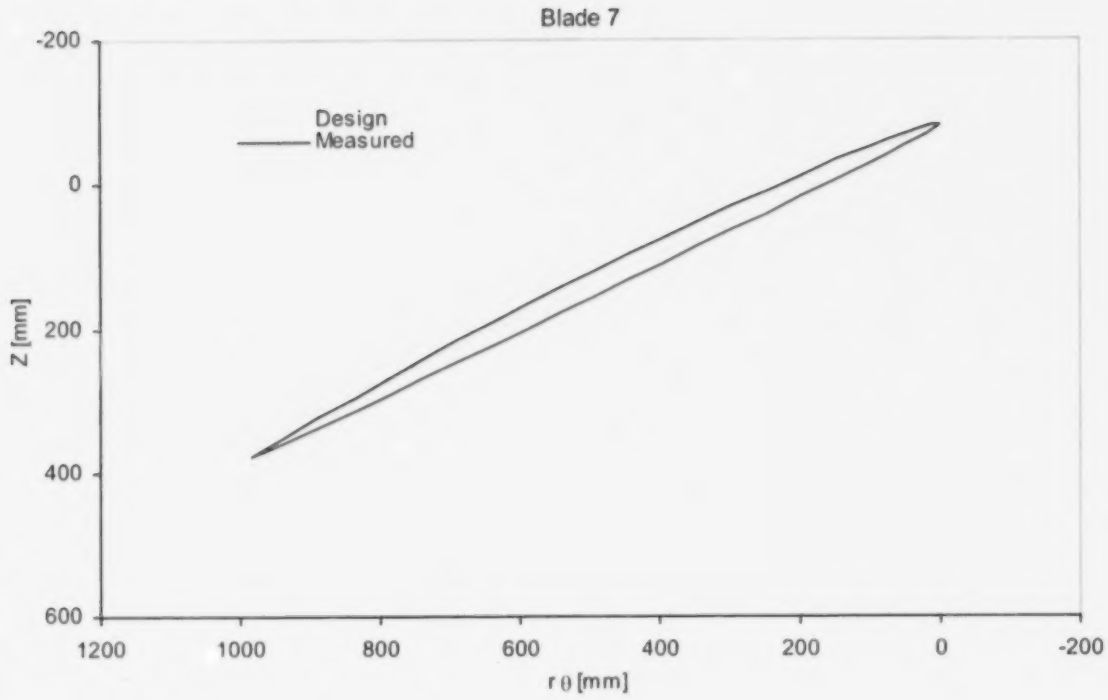


***Figure 30d**. Expanded Sections at a Radius Fraction of 0.90 for Blade 7 of the Starboard Propeller.*

Figures 31a through 31d for blade sections at r/R = 0.85 of the starboard propeller show slight over-pitching of less than one degree as obtained for the sections at 90 percent of the tip radius. These sections all have slightly smaller chord lengths relative to design with decreases in chord ranging from 5 mm on blade 2 to 19 mm on blades 1 and 5. As for sections at larger radii, these sections are all slightly over-raked with rake increases ranging from about 12 mm on blades 1 and 6 to 20 mm on blade 4 and the blade-to-blade variations in local thickness are not significant for these sections.

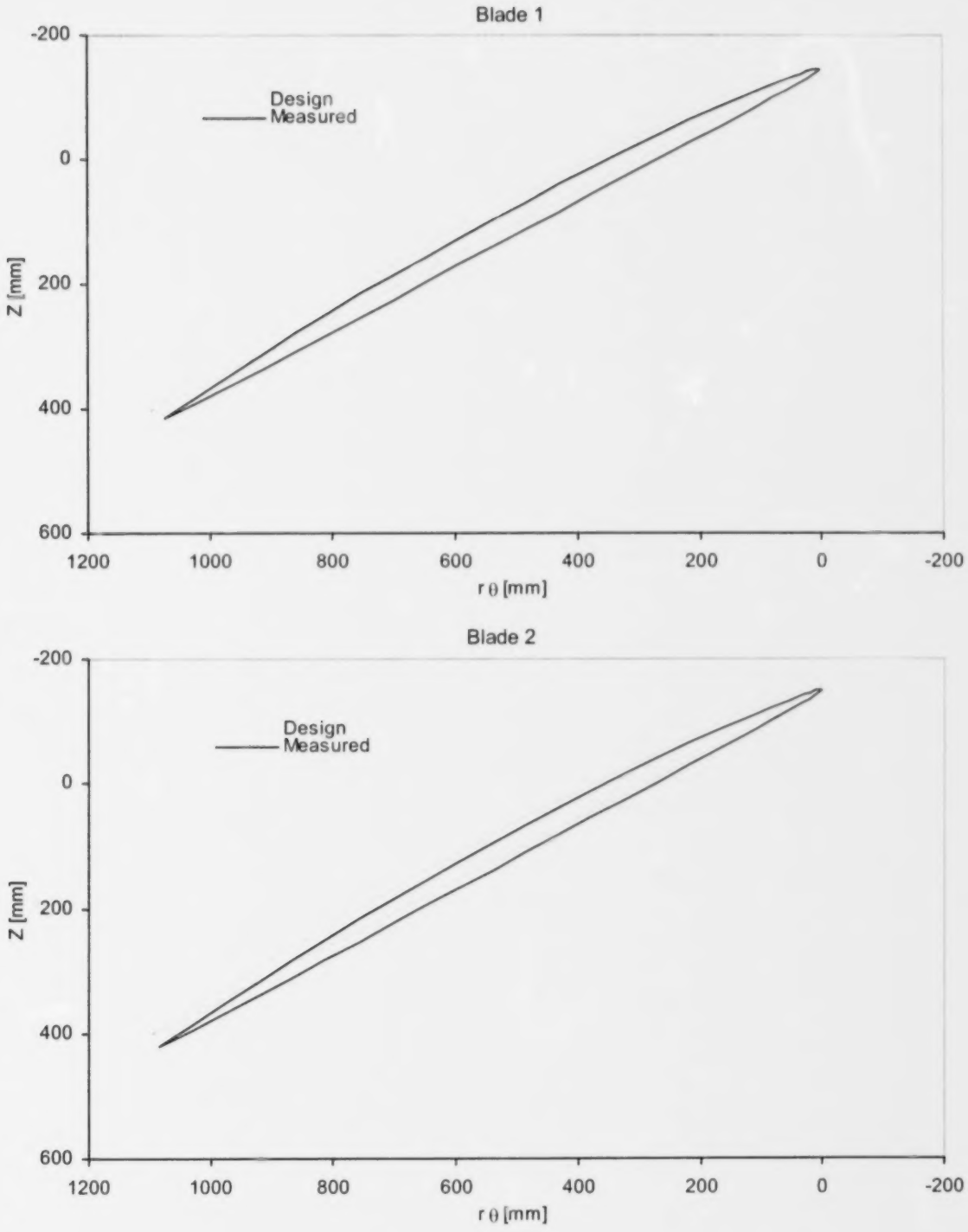


***Figure 31a**. Expanded Sections at a Radius Fraction of 0.85 for Blades 1 and 2 of the Starboard Propeller.*

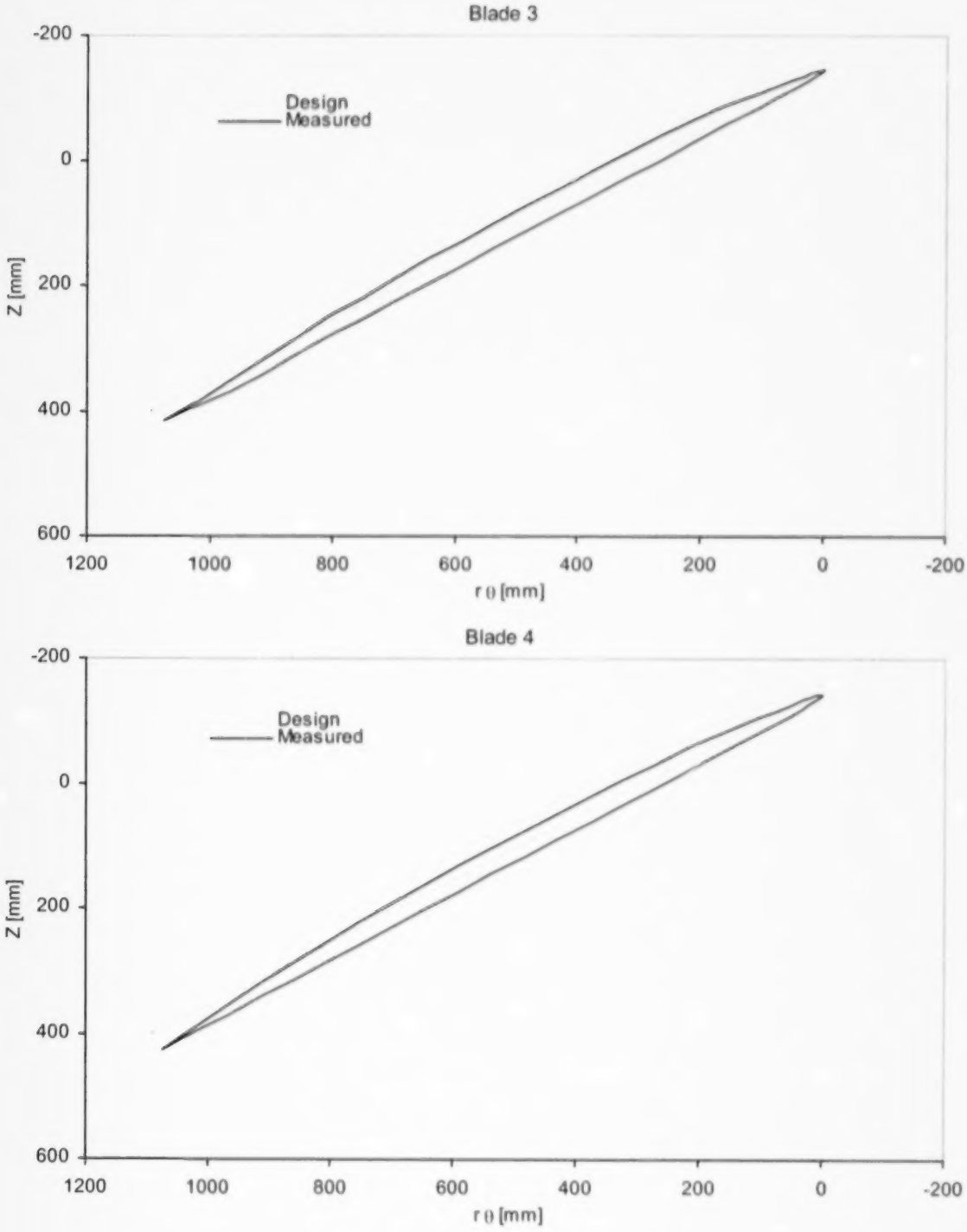


***Figure 31b**. Expanded Sections at a Radius Fraction of 0.85 for Blades 3 and 4 of the Starboard Propeller.*

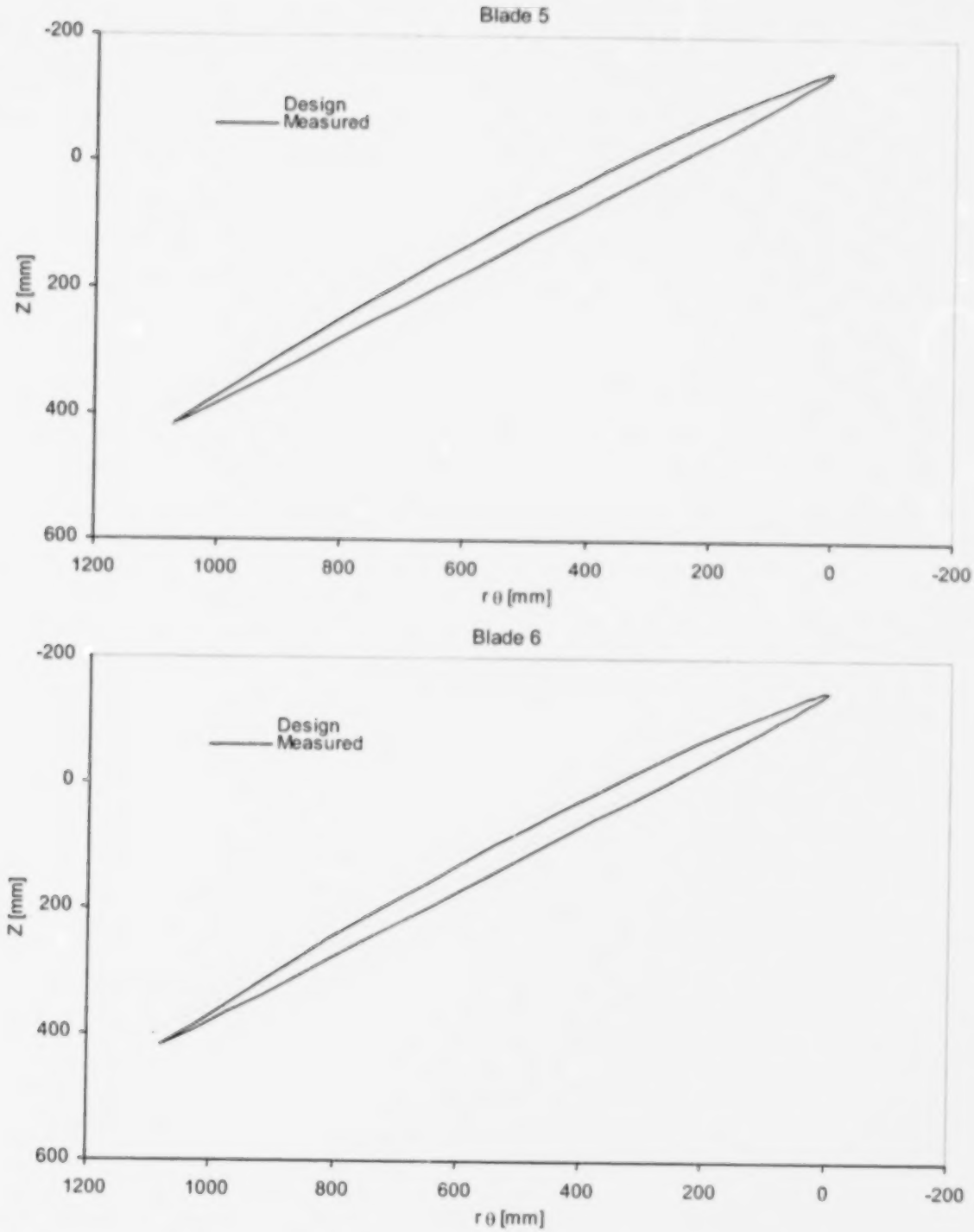


***Figure 31c**. Expanded Sections at a Radius Fraction of 0.85 for Blades 5 and 6 of the Starboard Propeller.*

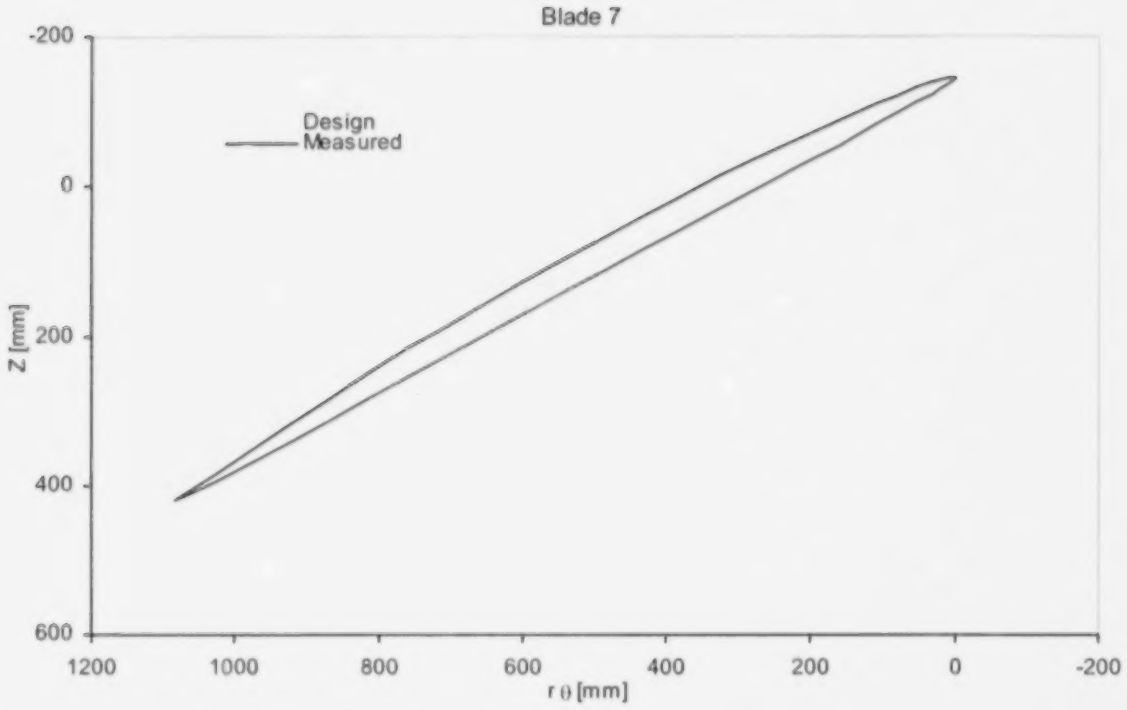


***Figure 31d**. Expanded Sections at a Radius Fraction of 0.85 for Blade 7 of the Starboard Propeller.*

Figures 32a through 32d for blade sections at r/R = 0.80 of the starboard propeller show slight over-pitching of less than half a degree. These sections all have slightly smaller chord lengths relative to design with very small decreases in chord ranging from less than a millimetre on blades 6 and 7 to almost 6 mm on blade 1. As for sections at larger radii, these sections are all slightly over-raked with rake increases ranging from about 9 mm on blade 1 to 13 mm on blade 4 and the blade-to-blade variations in local thickness are not significant for these sections.

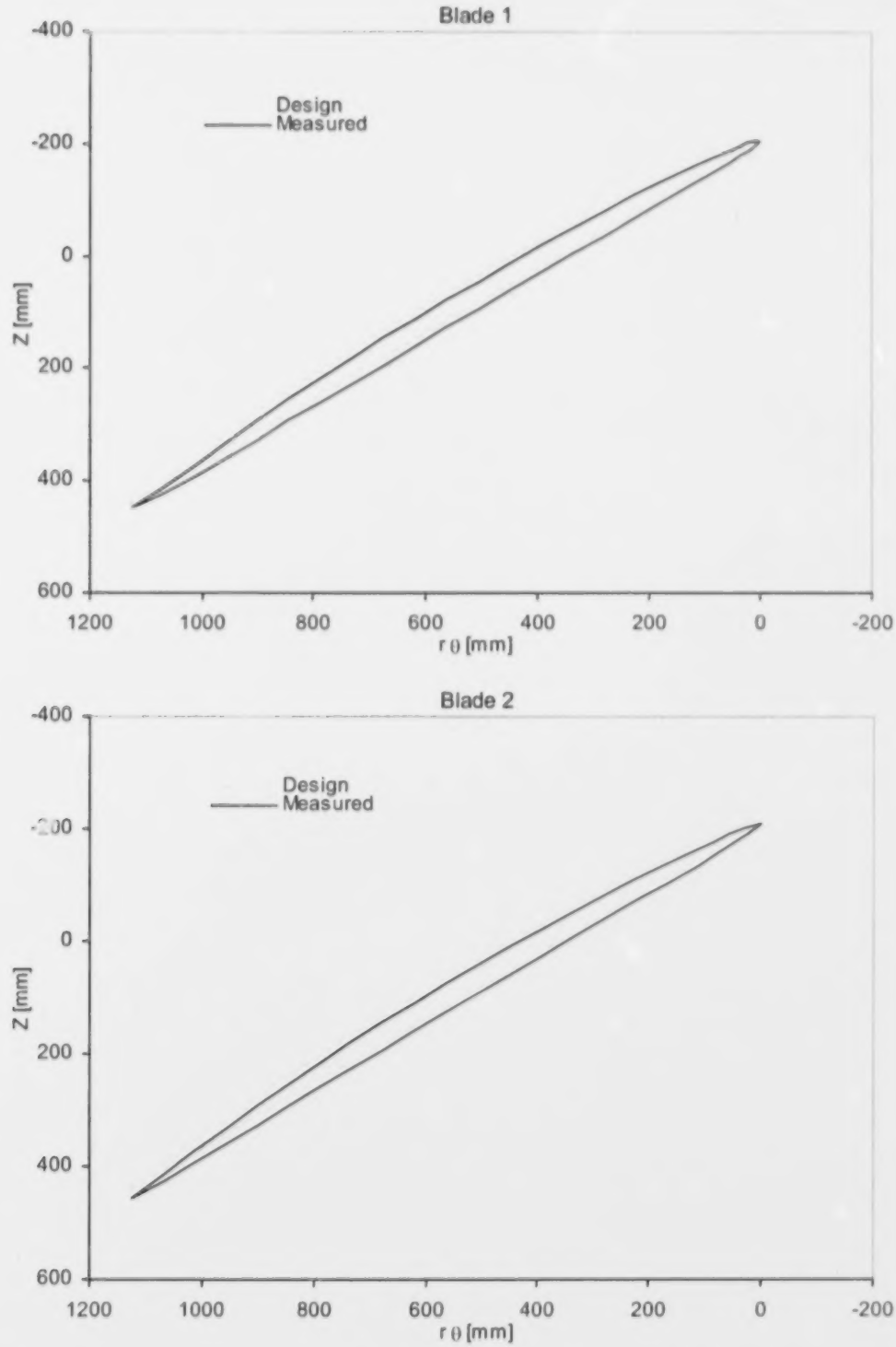


Figure 32a. Expanded Sections at a Radius Fraction of 0.80 for Blades 1 and 2 of the Starboard Propeller.

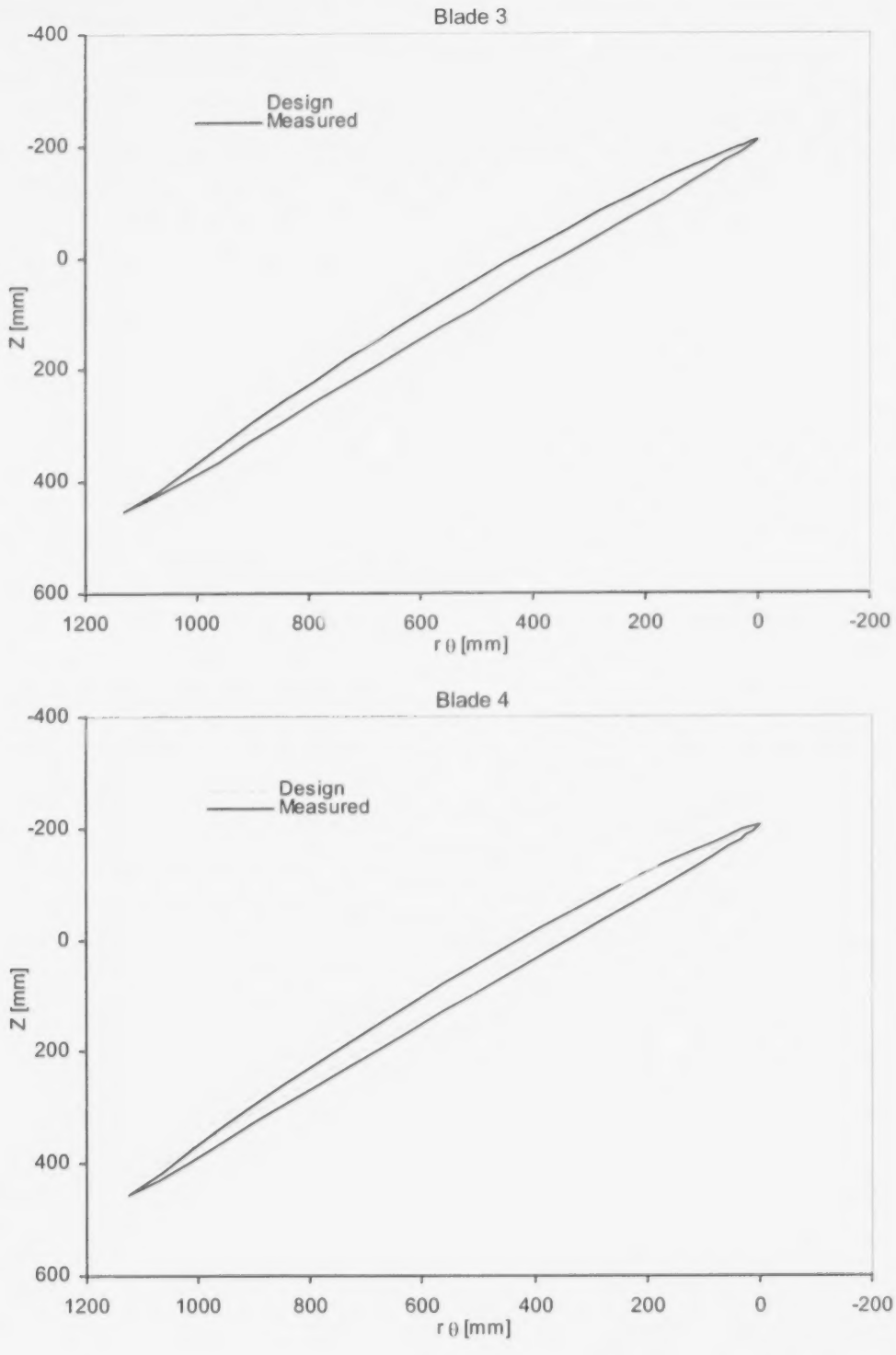


Figure 32b. *Expanded Sections at a Radius Fraction of 0.80 for Blades 3 and 4 of the Starboard Propeller.*

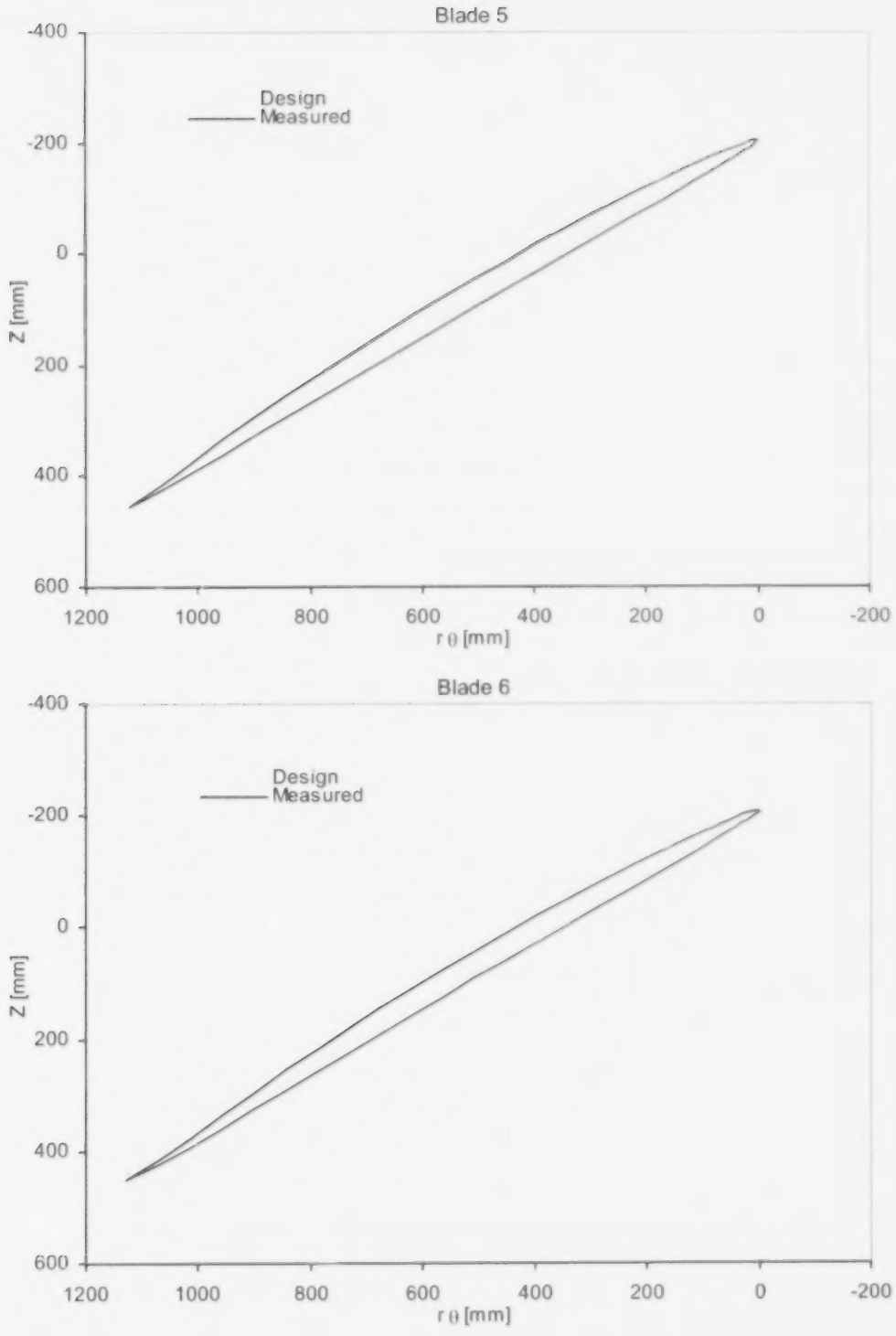


Figure 32c. *Expanded Sections at a Radius Fraction of 0.80 for Blades 5 and 6 of the Starboard Propeller.*

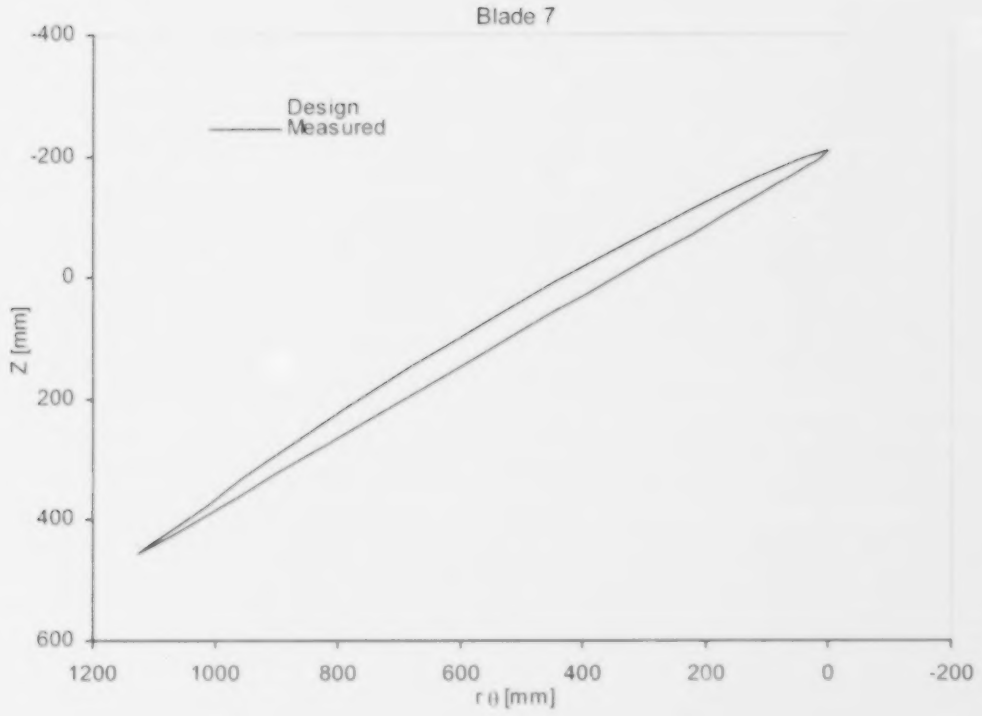


Figure 32d. *Expanded Sections at a Radius Fraction of 0.80 for Blade 7 of the Starboard Propeller.*

3.4 Leading Edge Shape Observations on Selected Blades

This final subsection of Section 3 describes the variations observed in nose shapes at the leading edges of outer radius blade sections resulting from a visual inspection of three selected blades of the port propeller. The nose shape variations described here are too close to the leading edges of the blades to be distinguished in the section surface plots provided in Section 3.3.

Blades 2, 3 and 5 of the port propeller were selected for leading edge shape observations since these were the blades observed during the sea trial on HMCS NIPIGON which examined changes to cavitation inception speeds both on a straight course and during turning circle manoeuvres. Blade 2 was selected for observations of leading edge vortex cavitation emanating from the leading edge and passing over the back or upstream side of sections just inboard of the tip, and was one of the first blades to start cavitating with increasing ship speed. Blades 3 and 5 were selected for observations of inception of attached back sheet cavitation occurring further inboard near the leading edge of sections at 70 to 80 percent of the tip radius, with blade 3 the last blade and blade 5 the first blade to start cavitating with increasing speed.

Figure 33 illustrates the radial extent of a leading edge flat observed on blade 2 of the port propeller drawn on a projected view of the blade looking upstream into the propeller rotation plane.

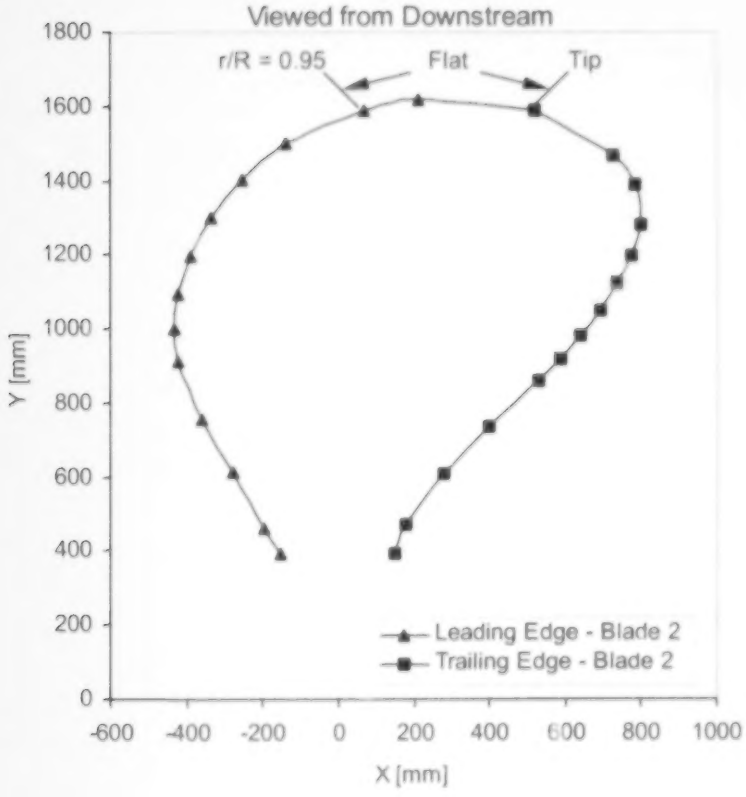


Figure 33. *Location of Leading Edge Flat Observed on Blade 2 of the Port Propeller.*

Figure 34 indicates the nose shape observed for the section at 95 percent of the tip radius on blade 2. In the figure, the location and size of the observed flat are indicated using a dashed line in a close-up of the expanded view of the measured section. The 3 mm width of the flat is seen to fall well within the chord interval between the first two points near the leading edge measured with the pitchometer. The smooth solid curve used for the nose shape in Figure 34 is a cubic spline through the measured surface points and is obtained with the same smoothed line option in Excel that was used to draw the section surface plots in Section 3.3. The smoothed solid line is a good representation of how the nose would have appeared without the flat. The same size flat extended outboard along the edge to the blade tip and produced a very sharp angled edge approaching the leading edge on the back surface. This is also the general location where leading edge vortex cavitation was observed to form on blade 2.

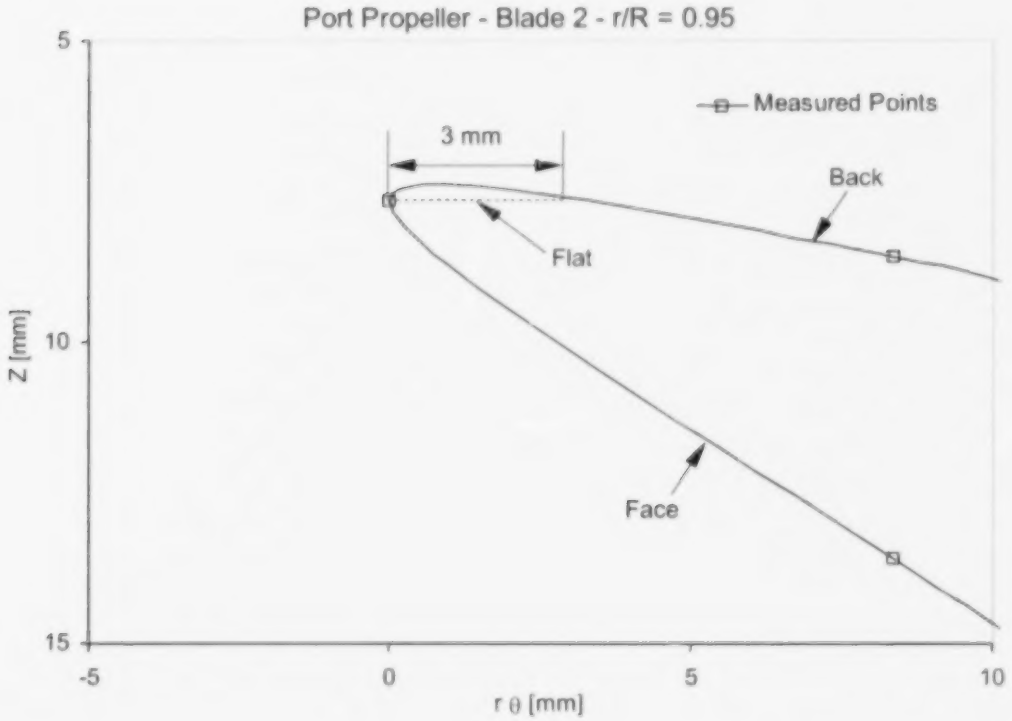


Figure 34. *Leading Edge Shape near Flat at r/R = 0.95 on Blade 2 of the Port Propeller.*

Figure 35 illustrates the radial extent of two different types of leading edge flat observed on blade 3 of the port propeller in the immediate vicinity of the tip. These flats are closer to the tip than the outermost section measured with the pitchometer. One flat decreases in width from about 3 mm at r/R = 0.98 to 2 mm at r/R = 0.99 and appears to be approximately normal to the edge on these tip sections. The second flat angles more towards the back surface like the flat illustrated in Figure 34 and decreases in width from about 2 mm at r/R = 0.99 to zero at the tip. The leading edge below this tip region was smoothly rounded as would be expected for design sections. This may explain why this blade had the highest inception speed for back sheet cavitation, a speed close to that predicted by both theory and model tests for the design blade.

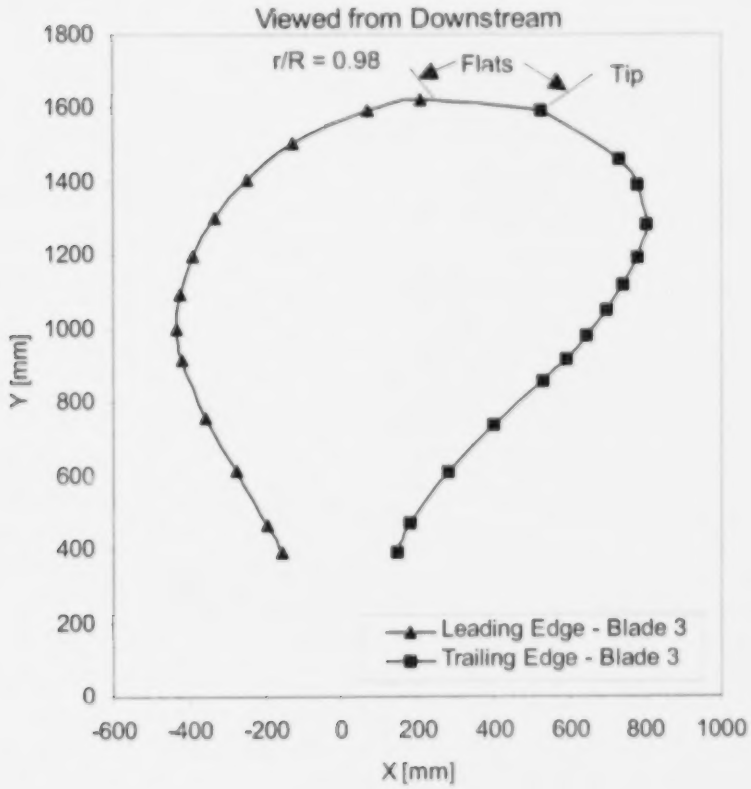


Figure 35. *Location of Leading Edge Flats Observed on Blade 3 of the Port Propeller.*

Figure 36 illustrates the radial extents for two types of edges observed on blade 5 of the port propeller, one very close to the tip in the same region as the flats in Figure 35 and one much further inboard near 70 percent of the tip radius. There is a flat between r/R = 0.98 and the tip having a width of about 1.5 mm and angled more towards the back surface. There is also a sharpened edge between 65 and 75 percent of the tip radius formed by about equally angled flats on both sides.

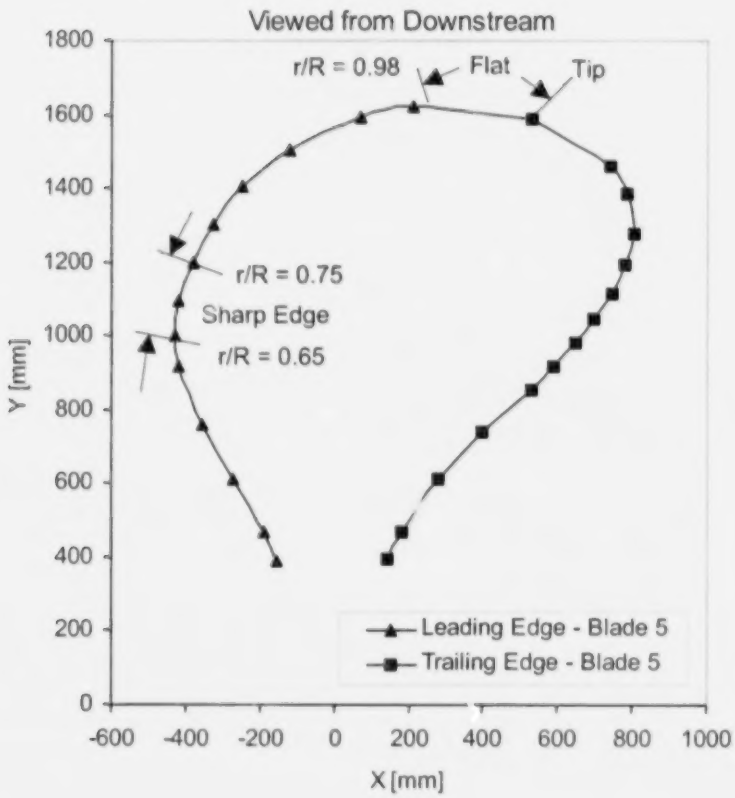


Figure 36. *Location of Leading Edge Flat and Sharp Edge Observed on Blade 5 of the Port Propeller.*

Figure 37 indicates the nose shape observed for the section at 70 percent of the tip radius. Again, the location and size of the observed flat is indicated using a dashed line in this close-up view of the measured section. This figure depicts a sharp leading edge formed by angled flats of about 3 mm width on both sides of the section. This is also the general location where attached back sheet cavitation was observed to form on blade 5, the blade for which this type of cavitation was observed to occur first with increasing ship speed.

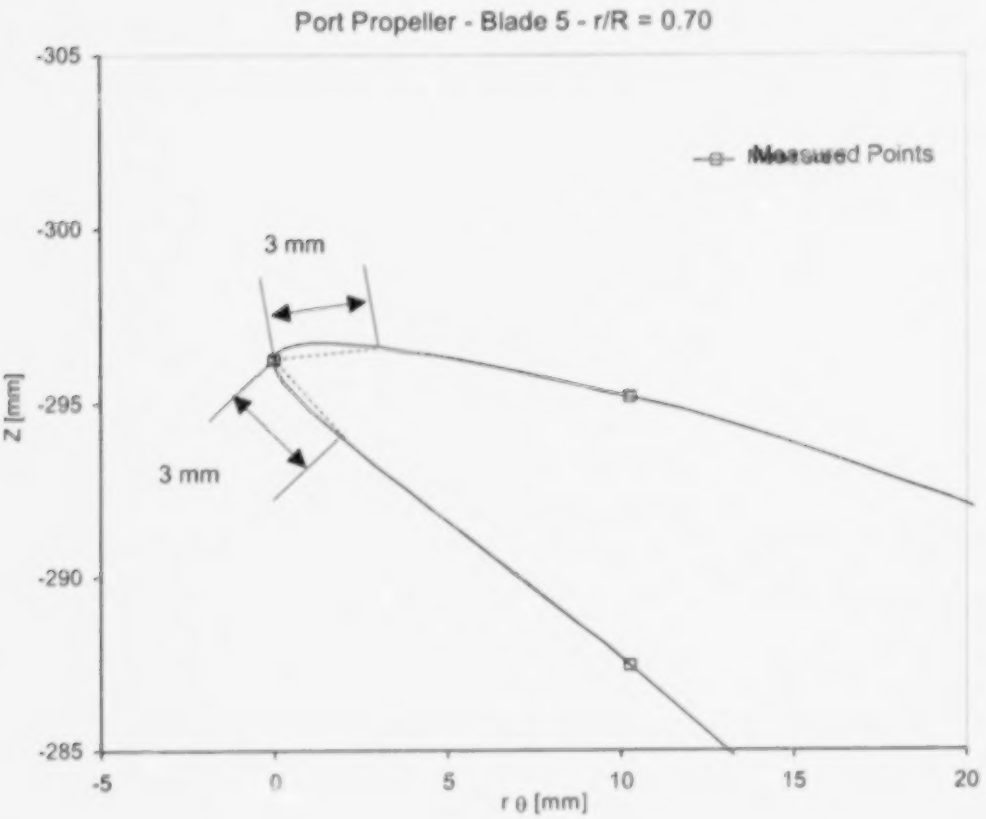


Figure 37. *Leading Edge Shape for Sharp Edge at r/R = 0.70 on Blade 5 of the Port Propeller.*

4. Discussion of Key Results

Section Pitch Angle

For the port propeller, outer radius blade sections were significantly over-pitched, reaching a maximum increase in pitch angle of 2.2 degrees or 11.2 percent of the design pitch angle at 97.5 percent of the tip radius on blade 2. Blade 6 was a close second, reaching a maximum over-pitch of 2.0 degrees or 10.2 percent on the same section. For the starboard propeller, the largest over-pitch of about 1.8 degrees or 9.4 percent was obtained at the 97.5 percent radius on blade 6. For the port propeller, inter-blade differences in pitch angle reached an absolute maximum of 1.4 degrees or 7.1 percent at the 97.5 percent radius. On the starboard propeller, the largest absolute difference in pitch angle between blades only reached a maximum of 0.4 degrees or 2.2 percent at the same radius.

The ISO Standard [1] for manufacturing tolerances of marine propellers of diameters greater than 2.5 m requires the mean pitch of sections at each measured radius to be within ±1 percent of design for Class S accuracy, the highest level of accuracy normally required of propellers manufactured for naval vessels. The other levels of accuracy defined for ISO Classes I, II and III require pitch tolerances of ±1.5, ±2 and ±5 percent, respectively. The ISO standards are requirements for newly manufactured blades. Blades with significant wear and damage would likely have areas that fall well outside these tolerances. Strictly speaking, their suggested tolerance requirements for pitch do not apply directly to the pitch angle but to the difference in the vertical (axial) distance between the leading and trailing edges. Even with this definition, the maximum pitch differences measured near the blade tips of the trialed propellers on HMCS NIPIGON fall well outside any of the ISO classes.

Section Chord Length

Chord length differences relative to design were largest approaching the tips of the starboard propeller blades reaching a maximum increase of 62.1 mm or 11.0 percent at 97.5 percent of the tip radius on blade 2. The same section on the port propeller had a maximum increase in chord length of 31.6 mm or 5.6 percent on blade 5. The port propeller also had the largest decrease in chord length of -45.6 mm or -5.5 percent of the design chord length at 95 percent radius on blade 6. Blade-to-blade differences in chord length reached an absolute maximum of 43.8 mm or 7.7 percent at the 97.5 percent radius of port propeller blades. The starboard propeller blades had a maximum absolute difference in chord length of 24.1 mm or 2.9 percent at the 95 percent radius while the maximum percentage difference of 3.1 percent occurred at the 97.5 percent radius.

The ISO standard specifies that differences in the length of blade sections expressed as a percentage of the value of the ratio of the propeller diameter to the number of blades should be within ±1.5 percent of design for Class S accuracy and within ±2, ±3 and ±5 percent for Classes I, II and III, respectively. Based on this definition, the largest chord length differences measured for the starboard propeller are about +13 percent and for the port propeller are -9 and +7 percent, well outside the ISO standards.

Section Skew Angle

Skew angle differences in degrees were all within one degree of design values on both propellers except for the tip of blade 4 of the port propeller where a maximum decrease in skew angle of 1.7 degrees was obtained. Inter-blade differences in skew angle reached an absolute maximum of 2.5 degrees or 13.2 percent at the tips of the port propeller blades, while the starboard propeller blades had a maximum inter-blade difference of about 1.2 degrees or 7.0 percent at the 97.5 percent radius. Tolerances on the skew of propeller blades are not part of the current ISO standard. The skew differences measured here are relatively small and should not affect the cavitation performance of these blades.

Section Total Rake

Both propellers were significantly over-raked over the outer 20 percent of their blades, with the largest over-rake of 36.4 mm occurring at the tip of blade 6 of the port propeller. For the starboard propeller, a maximum over-rake of 20.5 mm occurred at the 97.5 percent radius on blade 3. While all of the measured sections of the port propeller were over-raked, significant decreases in total rake were obtained for the root-most sections of the starboard propeller blades, reaching a maximum under-rake of 19.6 mm at the 25 percent radius on blade 2. While the maximum inter-blade difference in rake of 26.0 mm occurred at the tip of port propeller blades, a maximum difference of 13.8 mm occurred at the root-most section of starboard blades. Like skew, tolerance specifications for the rake of propeller blades are not included in the current ISO standard. Although these rake differences are significant, the axial displacement of sections as a whole should not affect the propulsion or cavitation performance significantly.

Expanded Blade Sections

Limitations in the accuracy of the pitchometer measurements were particularly evident for comparisons of the expanded blade sections. Small errors in the measured vertical distances to the blade surfaces resulted in the two sides of sections having a slight mismatch at their trailing edges. There were also small undulations in the smoothed curves that were fitted through the measured surface points on the thinner outer radius sections. The trailing edge errors were reduced by adjusting the vertical co-ordinates on each side equally to match the ultrasound thickness measured near mid-chord.

The validity of using a thickness adjustment obtained at mid-chord to correct the thickness over the entire section is questionable and may have been partly responsible for the large variations in thickness approaching the edges of outer radius sections. To obtain improved accuracy of propeller blade measurements in the future, vertical measurement accuracy would need to be improved possibly with the use of optical scanning devices rather than surface contact with the long metal pointers of the pitchometer.

Leading Edge Shape Observations

Three blades of the port propeller were examined visually for variations in the shapes of their leading edges at locations where cavitation was observed to form during the sea trial. These blades had the lowest inception speeds for leading edge vortex cavitation forming just inboard of the blade tip, and the lowest and highest speeds for inception of attached back sheet cavitation forming further inboard along the leading edge near sections at 70 percent of the tip radius. The flats observed on the worst performing blades produced much thinner and sharper leading edges than the design sections.

A measuring device capable of better resolving the leading edge nose shapes is required. It may be possible to measure the leading edges with a high resolution, optical scanner. The ISO Standard for a Class S and I accuracy of the final detail of section leading edges suggests that propeller manufacturers use special leading edge templates composed of three parts. Separate back and face fairing templates are suggested covering each side of the section from the end of the nose region to about 20 percent of the chord length, together with a special nose template made to design size plus the maximum tolerance and covering approximately the first 5 percent of the chord length on both sides. Each part should fit within a maximum surface tolerance of 0.25 mm and 0.35 mm for Classes S and I, respectively.

5. Conclusions

This report has presented results from the detailed measurements of the surface geometry of the propeller blades of HMCS NIPIGON conducted by FMF Cape Scott between May and December 2000 at the request of DRDC Atlantic. Pitchometer and ultrasound thickness measurements were used to compare the geometry of measured blades to each other and to the design blade geometry. The geometric differences described here can be used to help explain the abnormally large differences in cavitation performance obtained for different blades during a sea trial performed in October 1997 for the CRNAV Project on In-Service Propeller Performance. The following conclusions result from the blade measurement program.

Relative to design, the largest differences in blade geometry were obtained for blade sections in the outer 20 percent of the blades with the differences in key geometric parameters generally increasing to a maximum moving towards the tips. Of the differences defined for pitch angle, chord length, skew angle and total rake of measured sections, the pitch angle differences are likely to have the largest influence on cavitation performance. These propellers had many years of service prior to the cavitation viewing trial in October 1997, and the blades likely accumulated significant surface wear and damage since they were originally installed on HMCS NIPIGON. The geometric differences relative to design obtained for outer radius blade sections are well outside any of the current ISO standards for newly manufactured blades.

While the blades of both propellers had significant geometric differences for outer radius sections compared to the design geometry, the blade-to-blade differences were significantly larger on the port propeller. The large inter-blade pitch differences would generate a wide range of inception speeds for cavitation forming near the tips of different blades. The large inter-blade variations in chord length and rake of blade sections approaching the tips of both propellers were largely responsible for the significant differences in the shapes of the outer edge outlines of the blades observed during the brief inspection prior to the sea trial. These chord and rake variations are not likely to influence cavitation performance in any significant way.

The limitations of the pitchometer device for detailed measurements of propeller blades are evident from the results of this measurement program. FMF Cape Scott has an optical scanning device that is used to accurately measure and verify the tolerances of machinery parts and other surfaces up to about a metre in size. Larger scanning devices would be needed to measure naval surface ship propellers that are typically 3 to 4 metres in diameter. These devices would need to be accurately positioned relative to the blades, and the measurements converted to a hub-centred cylindrical coordinate system for comparison with the design geometry. A digital display and direct input of measured coordinates to computers would significantly reduce the time required to perform the measurements of a fine grid of surface points, particularly around the tips and leading edges of the blades.

The variations observed in the leading edge nose shapes of three port propeller blades likely contributed to the large differences in cavitation inception speeds observed on these blades during the sea trial on HMCS NIPIGON. The pitch increases alone would have caused decreases in the inception speeds of both attached back sheet and tip vortex types of cavitation due to the resulting increases in angle of attack of sections and decreases in

pressure at the leading edge. The sharp wedge-shaped leading edge observed on outer sections of blade 2 of the port propeller could have generated flow separation and replaced any sheet and tip vortex cavitation with the cavitating leading edge vortex observed on the sea trial. Additionally, the sharpened nose observed at the leading edge of sections near 70 percent of the tip radius on blade 5 of port propeller could have led to inception of attached back sheet cavitation at this location at much lower speeds. Blade 3 of the port propeller, having the highest inception speeds for back sheet cavitation at this location and the closest to design expectations, was observed to have a smoothly rounded leading edge except for tipmost sections outboard of the 97.5 percent radius.

It would be difficult to verify through model scale experiments whether the geometric differences described in this report were entirely responsible for the cavitation inception speed reductions observed on the NIPIGON trial. The ability to generate flow separation and form cavitating vortices along the leading edges of propeller blades at the same locations observed on the sea trial would be strongly dependent on Reynolds Number. It would not likely be possible to generate leading edge vortex cavitation with scale models of propellers due to Reynolds Number scaling effects that cause sheet cavitation to occur first at the same locations with increasing speed.

Analytical prediction methods for propellers operating in a ship's wake are still not capable of predicting the dominant viscous flow effects generated by the types of geometric differences measured on these blades. Numerical prediction of inception speeds for tip or leading edge vortex cavitation would require further development and validation of turbulence modeling for rotating blade boundary layer and wake vortex flows in current Reynolds-Averaged Navier-Stokes (RANS) solvers for unsteady flow as well as the use of significant computer resources. Evaluation of the effects of leading edge flats and sharpened edges would require modeling of viscous flow effects including the onset of flow separation. It should be possible, however, to use current prediction tools for potential flow to examine the effect of pitch angle differences on inception of sheet cavitation near the blade tips.

6. References

1. International Organization for Standardization. (1981) Shipbuilding – Ship screw propellers – Manufacturing tolerances – Part 1 : Propellers of diameter greater than 2.50 m. ISO 484/1-1981 (E)

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This report describes results obtained for the differences in the blade geometry of the propellers of HMCS NIPIGON based on detailed blade measurements performed with a pitchometer and ultrasonic thickness measuring equipment. Visual inspection of the blades made while the ship was in dry dock for a previous sea trial revealed signs of significant surface wear and damage. The measurements were requested by DRDC Atlantic after the ship went out of service to determine if the geometric differences between the blades of each propeller could have caused the unexpectedly large differences in the cavitation inception performance of individual blades observed during the sea trial.

The results show significant differences in the key geometric parameters of blade sections, especially in the pitch angle, chord length and rake of measured sections at outer radii. Of the section differences obtained from the blade measurements, the pitch angle increases of more than two degrees relative to design approaching the blade tips are expected to have the largest effect on inception of cavitation in this region. Examination of the nose shapes of the leading edges on selected blades also revealed flats and overly sharp edges near locations where cavitation was observed to form during the sea trial. The sharpness of the leading edges can also have a significant effect on inception speeds, and is likely the cause of the flow separation and formation of vortex cavitation observed along the leading edges of the blades.

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